Aalto University
School of Electrical
Engineering

Noora Jaakamo

Impact of the 15-Minute Imbalance Settlement Period and Electricity Storage on an Independent Wind Power Producer

Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Technology.
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Supervisor: Professor Sanna Syri
Advisor: DI Petter Sund

Aalto University
School of Electrical Engineering

Aalto University, P.O. BOX 11000, 00076 AALTO
www.aalto.fi

Abstract of master's thesis

Author Noora Jaakamo

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Abstract

The popularity of intermittent renewable energy sources and electricity storages is increasing. As a response to increasing intermittent renewable energy generation, the Finnish transmission system operator Fingrid plans to introduce a 15-minute imbalance settlement period and several other changes on the Finnish electricity market in the near future.

The goal of this thesis is to study the effect of the 15-minute imbalance settlement period together with other market changes and the profitability of electricity storage from the viewpoint of an independent wind power producer. The study is performed by analysing the day-ahead, intraday and balancing power markets in Germany and Finland. Also, Finnish FCR-N markets, wind power production and forecast data and production data from some Finnish wind turbines is investigated.

The main findings are that balancing costs of Finnish wind power production are currently low, however, in the near future the 15-minute imbalance settlement period will encourage power producers to shift from paying balancing fees to participating actively on the intraday markets. The intraday markets will likely have a particular shape in which the first and last quarter have the highest and lowest prices and highest volumes, and the pricing will likely be unfavourable for a wind power producer. However, intraday prices could be, to some extent, predictable from day-ahead prices.

Another main finding is that the current amount of wind power decreases electricity market prices only slightly, but the risk of price cannibalization might increase in the future. Wind power production in Finland seems geographically heterogeneous and the risk of cannibalization can be affected by an appropriate distribution of wind farms.

The last main finding is that an electricity storage is profitable on the current hourly FCR-N market if charged occasionally with excess wind power resulting from erroneous wind power forecasts. The profitability of an electricity storage increases for a wind power producer in the next few years when the 15-minute imbalance settlement period is implemented and the share of wind power in the Finnish power system increases.

Keywords 15-minute imbalance settlement period, electricity markets, wind power, renewable energy, electricity storages

Aalto-yliopisto
Sähkötekniikan korkeakoulu

Aalto-yliopisto, PL 11000, 00076 AALTO
www.aalto.fi
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Tiivistelmä

Vaihtelevat uusiutuvat energianlähteet ja sähkövarastot kasvattavat suosiotaan. Vastatoimena lisääntyville uusiutuville energianlähteille Suomen kantaverkkoyhtiö Fingrid suunnittelee viidentoista minuutin taseselvitysjakson eli varttitaseen ja monen muun uudistuksen käyttöönottoa sähkömarkkinoilla lähitulevaisuudessa.

Tämän työn tavoitteena on tutkia varttitaseen ja muiden sähkömarkkinauudistusten vaikutusta sekä sähkövaraston taloudellista kannattavuutta itsenäisen tuulivoimatuottajan näkökulmasta. Tutkimus toteutetaan tarkastelemalla vuorokausi-, päivänsisäisiä ja säätösähkömarkkinoita Saksassa ja Suomessa. Lisäksi Suomen FCR-N markkinoita, tuulivoiman tuotantoa ja tuotantoennustetta sekä yksittäisten suomalaisten tuulivoimaloiden tuotantodataa tutkitaan.

Tutkimustulokset viittaavat siihen, että tällä hetkellä tuulivoiman tasevirheestä maksaminen on edullista, mutta lähitulevaisuudessa varttitase tulee rohkaisemaan voimantuottajia siirtymään tasevirheiden maksamisesta kaupankäyntiin päivänsisäisillä markkinoilla. Päivänsisäisillä markkinoilla tulee mahdollisesti olemaan muoto, jossa kunkin tunnin ensimmäisellä ja viimeisellä vartilla tulee olemaan korkeimmat ja alhaisimmat hinnat, ja tämä muoto tulee todennäköisesti olemaan epäsuotuisa tuulivoiman tuottajalle. Päivänsisäisten markkinoiden hinnat tulevat kuitenkin mahdollisesti olemaan jokseenkin ennustettavissa vuorokausimarkkinahinnoista.

Tutkimustulokset indikoivat, että nykyinen tuulivoiman tuotannon määrä laskee vain hivenen sähkömarkkinahintoja, mutta tulevaisuudessa on riski kannibalisaatiolle. Tuulivoiman tuotanto vaikuttaa Suomessa kuitenkin maantieteellisesti heterogeeniseltä ja kannibalisaation riskiin voidaan vaikuttaa tuulivoimaloiden asianmukaisella hajauttamisella.

Viimeinen tutkimustulos osoittaa, että sähkövarasto on kannattava nykyisillä FCR-N tuntimarkkinoilla, jos sitä ladataan silloin tällöin virheellisen tuulivoimaennusteen aiheuttamalla ylimääräisellä tuulivoimalla. Sähkövaraston hyöty tuulivoiman tuottajalle kasvaa lähivuosina varttitaseen käyttöönoton ja Suomen tuulivoimatuotannon kasvun johdosta.

Avainsanat varttitase, sähkömarkkinat, tuulivoima, uusiutuva energia, sähkövarastot

Acknowledgements

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Noora Jaakamo

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Nomenclature

R	Correlation coefficient / correlation
R^2	Coefficient of determination / square of correlation
r	Interest rate

Abbreviations

aFRR	Automatic Frequency Restoration Reserve
AL-TES	Aquiferous Low-temperature Thermal Energy Storage
BESS	Battery Energy Storage System
BRP	Balance Responsible Party
CAES	Compressed Air Energy Storage
CES	Cryogenic Energy Storage
DR	Demand Response
DSO	Distribution System Operator
EEX	European Energy Exchange
EPEX SPOT	European Power Exchange
FCR	Frequency Containment Reserve
FCR-D	Frequency Containment Reserve for Disturbances
FCR-N	Frequency Containment Reserve for Normal Operation
FES	Flywheel Energy Storage
FRR	Frequency Restoration Reserve
HT-TES	High-Temperature Thermal Energy Storage
IDSM	Industrial Demand-Side Management
IRENA	International Renewable Energy Agency
ISP	Imbalance Settlement Period
ISR	Imbalance Settlement Responsible
LCOE	Levelized Cost of Electricity
LTO	Lithium Titanate
MARI	Manually Activated Reserves Initiative
MBA	Market Balance Area
mFRR	Manual Frequency Restoration Reserve
MGA	Metering Grid Area
MTU	Market Time Unit
NBM	Nordic Balancing Model
NEMO	Nominated Electricity Market Operator
O&M	Operations and Maintenance
PHS	Pumped Hydro Storage
PICASSO	Platform for the International Coordination of the Automatic Frequency Restoration Process and Stable System Operation
PPA	Power Purchase Agreement
RE	Retailer
RR	Replacement Reserve
RSD	Relative Standard Deviation
SMES	Superconducting Magnetic Energy Storage
SP	Service Provider
TSO	Transmission System Operator
WACC	Weighted Average Cost of Capital

1 Introduction

Wind power has become increasingly cost-competitive over the last years and is currently profitable without any subsidies. This has enabled a significant increase in wind power production, which is likely to grow even more in the near future. (*Suomen Tuulivoimayhdistys ry,* 2019)

However, several challenges related to an increasing share of wind power are foreseen for a wind power producer. Wind power production is intermittent and challenging to forecast precisely. The difficulties in forecasting amplify the effect of balancing costs. Also, large amounts of wind power may affect electricity prices which could have an impact on the profitability of wind power.

The electricity markets are facing significant changes since the 15-minute imbalance settlement will be implemented in the next years in Finland. The major reason behind this is to reduce net system imbalances despite the increasing intermittent renewable energy generation and enable market coupling between European countries. This may revolutionize the electricity market making it thus essential for a wind power producer to estimate its impact.

Several potential solutions are available for a wind power producer to even out its production, one being the electricity storage. Electricity storages have increased their popularity over the last years and have become increasingly attractive.

The goal of this thesis is to estimate the effect of the upcoming electricity market changes such as the 15-minute imbalance settlement period and increasing intermittent renewable energy share together with an electricity storage on an independent wind power producer. The estimations are done for the present and future scenarios. For simplicity, this study focuses on lithium-ion batteries, since they are one of the cheapest and most popular battery energy storages. The scope of this thesis is limited to the view of an independent wind power producer and the geographical focus is on Finland.

The main research questions of this thesis are as follows:

- How does the upcoming 15-minute imbalance settlement period change the electricity market prices and trading behaviour in Finland?
- Does the increase of intermittent renewable energy sources, particularly wind power, affect their profitability and how can the effect be minimized?
- How profitable is wind power now and in the future, if forecast errors are taken into consideration?
- Is an electricity storage profitable now and in the future, and how does combining the storage with wind power production change the scenario?

This thesis first presents the basics of the Nordic electricity markets followed by a description of wind power's main challenges and their mitigators and an overview of the upcoming changes in the Nordic electricity markets. To understand the effects of the new electricity market environment from a wind power producer's perspective, various market and wind power production data is analysed. The effect of the 15-minute imbalance settlement period is examined by comparing historical day-ahead, intraday and balancing market data in Finland and Germany and by investigating the relationship between German intraday and day-ahead prices. The effect of increasing variable renewable energy sources is examined by analysing the correlation between the wind power production of a single and all wind turbines in Finland and investigating the correlation of wind power production and forecast errors with the intraday and balancing market prices and volumes. The profitability of wind power is analysed on the current day-ahead market and the profitability of electricity storages is analysed on the current FCR-N market. The feasibility of their combination now and in the near future is estimated based on both day-ahead and FCR-N markets and investigations on the new market environment.

2 Theoretical Background – The Nordic Electricity Market

Electricity can be sold via Power Purchase Agreement (PPA) projects or merchant projects. PPA projects have an agreed price per kWh between the seller and the buyer. Merchant projects take part in the Nordic electricity markets. Compared to PPA projects, merchant projects have a lower certainty of cashflow, but the revenue is usually higher and thus the payback period is often shorter. Chapter two focuses on merchant projects, presenting the Nordic electricity market structure. (Grover, Torgoman and Touma, 2018)

Before the 1990's, the Nordic electricity markets functioned within each countries' borders. The journey towards a unified Nordic market began in 1992 when the Norwegian Transmission System Operator (TSO) Statnett was established. Later that year, Statnett established the Nord Pool Spot market, which was joined by Finland in 1998, Western Denmark in 1999 and Eastern Denmark and Sweden in 2000. Since 2001 the transmission between the Nordic countries has been charge free. (Ma, Prljaca and Jorgensen, 2016)

The current Nordic electricity market, presented in Figure 1, consists of several separate markets that are linked to each other. Separate markets enable a cost-efficient, secure and high-quality electricity supply that responds to the electricity demand. The markets prior to electricity delivery hour include the financial, day-ahead (elspot) and intraday (elbas) market. Elspot and elbas are bilateral trades. On the delivery hour occurs the balancing and reserve market. Balancing market is also known as the regulating market. After delivery, imbalance settlement is calculated. Of these, Nord Pool provides an energy-only trading platform for the financial, day-ahead, intraday and balancing power market. The reserve market is provided by the local TSO, which is Fingrid in Finland, and the imbalance settlement is provided by eSett in Finland, Norway and Sweden. (Ma, Prljaca and Jorgensen, 2016)

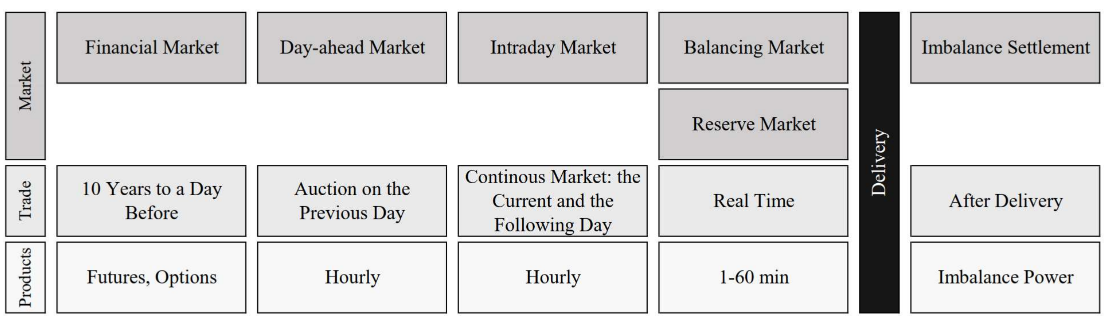

Figure 1 Nordic electricity market structure, modified from Fingrid (2019d)

2.1 Financial, Day-Ahead and Intraday Market

The financial market is a market long before delivery, from weeks to years before, by which major electricity consumers and suppliers can avoid the risk of a volatile system price. A supplier might seek protection from low prices and a major consumer from high prices. Electricity is traded with futures, forwards and options. (Amundsen and Bergman, 2006)

The day-ahead market is carried out through Nord Pool power exchange with hourly system prices. The day-ahead price is formed daily on the day before delivery. The deadline for suppliers to submit orders is 12:00 CET. After that, all purchase and sell orders are aggregated into curves for each delivery hour of the next day. The market consists of separate geographical price (bidding) areas. If transmission capacity is insufficient, the area prices differ from the system price. Price areas can have a balance, deficit or surplus of electricity. Norway divides into five, Sweden into four, Denmark into two and Finland into one price area. (Amundsen and Bergman, 2006, *Nord Pool,* 2017)

The intraday market opens after the day-ahead market and aims to fill in the gaps between the day-ahead market and the forecast made close to delivery. The capacities available for intraday trading are published at 14:00 CET. The intraday market closes 60 minutes before delivery in Norway, Sweden, Denmark, Lithuania and Latvia, 30 minutes before the delivery hour in Germany, France, Estonia, Austria and Finland and 5 minutes before in the Netherlands and Belgium. Cross-border connections close 60 minutes before delivery, except for the connection between Estonia and Finland closes 30 minutes before delivery. (*Nord Pool,* 2018)

2.2 Reserves and Balancing Power

Balancing- and reserve markets aim to even out sudden frequency dips or peaks by maintaining the optimal frequency of 50 Hz. It can be achieved by evening out sudden changes in production and consumption. The Nordic countries have agreed on the total amount and major obligations for each country's balancing- and reserve markets. However, these markets are national and therefore Nordic countries have some differences in their systems and rules for bidding and payment. In Finland, the market occurs as few as seconds to 15 minutes before delivery. (*Fingrid,* 2014)

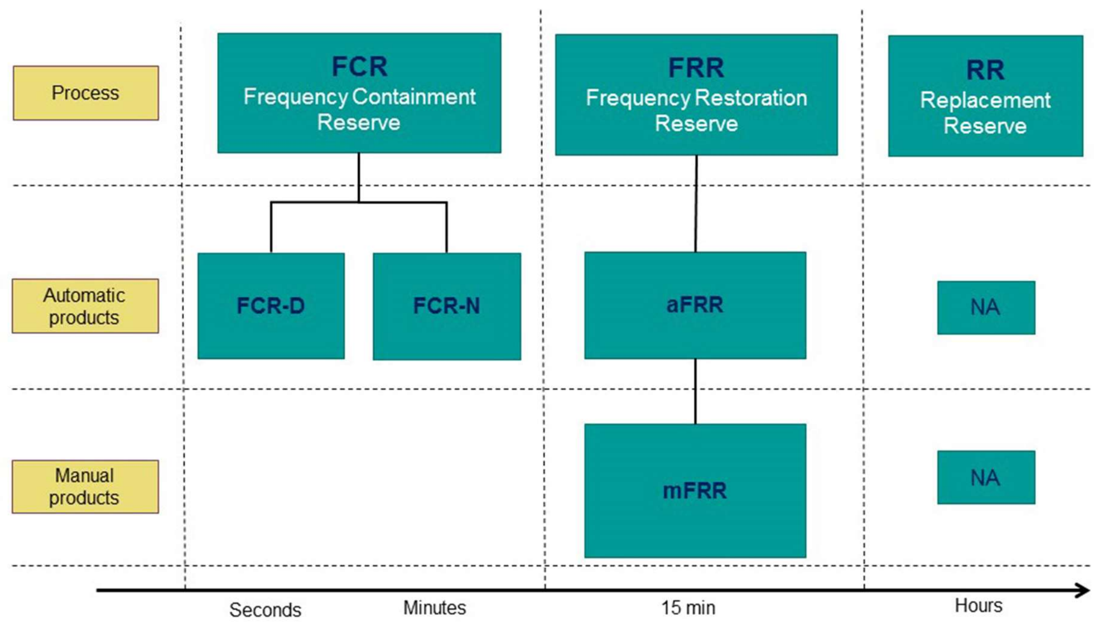

Figure 2 Reserve products in Finland (*Fingrid,* 2014)

Reserve products provided by the Finnish TSO Fingrid are presented in Figure 2. They contain frequency containment reserves (FCR), frequency restoration reserves (FRR) and replacement reserves (RR). FCRs divide in two: the frequency containment reserve for normal operation (FCR-N) and frequency containment reserve for disturbances (FCR-D). Also, FRRs divide into two: automatic frequency restoration reserve (aFRR) and manual frequency restoration reserves (mFRR). (*Fingrid,* 2014)

FCRs are used for constant frequency control. The power is traded via yearly and hourly markets. In yearly markets, the bidding competition is organized yearly every autumn, and it is not allowed to take part later. Production plans are left on the previous day by 6 pm. There is a fixed price all year, which is determined by the highest accepted offer price. In the hourly markets, the reserve holder can take part in any time of the year and no yearly contract is required. The offers are used in price order, cheapest first. The offers for the next day need to be submitted by 6.30 pm. The price for each hour depends on the most expensive offer used in the hour. (*Fingrid,* 2017)

The FCRs are divided to DCR-N and FCR-D. FCR-N reacts constantly and automatically to slight local frequency deviations in only a couple of minutes. FCR-N is able to both increase or decrease power. FCR-N is traded via an hourly market. Both the capacity available and the actual activated net energy is compensated. The compensation of FCR-N yearly market is around 14 €/MW/h and hourly market is around some dozens of €/MW/h. The minimum capacity is 0.1 MW. (*Fingrid,* 2014)

FCR-D reacts automatically to significant local frequency deviations that are often caused by disturbances. FCR-Ds are able to be activated in 5 or 30 seconds, and they have an option to take part also in 1, 3, or 5 second activation periods, of which 1 second corresponds a frequency drop down to 49,5 Hz, 3s 49,6 Hz and 5s 49,7 Hz. FCR-D only needs to provide up-regulation, which means increasing power production or decreasing power consumption. Down-regulation would mean the opposite. The trade is performed in the hourly market, with payments for the available capacity. The compensation is in the yearly market around 3€/MW/h and in the hourly market around some dozens of €/MW/h. The minimum capacity is 1 MW. (*Fingrid,* 2014)

FRRs step in soon after FCRs to release the FCRs back into use. The aFRRs take action continually and within a couple of minutes of the automatic activation signal sent by Fingrid. They participate in an hourly market and are compensated by their capacity available and the activation. Capacity payment is around dozens of €/MW/h and activation payment is similar to the balancing energy market price. The minimum capacity is 5 MW. Today aFRRs are procured only for some hours of day. (*Fingrid,* 2014)

The mFRRs divide into balancing energy markets, fast disturbance reserves and balancing capacity markets. The Fingrid's balancing energy markets take part in the Nordic balancing energy markets. Bids are activated in price order and delivered or updated up to 45 minutes before the delivery hour. The balancing markets include both up- and down-regulation bids that need to be able to activate in 15 minutes. The compensation for balancing energy is calculated by the ordered energy and the most expensive bid used in the hour. The price is always better than the elspot price, and it might even rise up to hundreds or thousands of €/MWh/h. The minimum capacity is 10 MW for a phone call order or 5 MW for an electrical order. (*Fingrid,* 2014)

Fast disturbance reserves are secured 15-minutes up-regulation capacities. They include Fingrid's own reserve power plants and some long-term contracts with other reserve power plants that are not used in electricity markets. The Nordic TSOs have agreed that each country needs to have enough reserves for their own dimensioning faults in every part of the system. The total demand for fast disturbance reserves in Finland varies usually at 880 to 1100 MW. (*Fingrid,* 2014)

Fingrid's balancing capacity markets secure the necessary up-regulation capacity also when the reserve power plants are unavailable. The capacity is procured in bidding competitions weekly. The service provider whose bid is selected needs to deliver the up-regulation bids on the previous day at 1 pm. The balancing capacity bids are used on the balancing market after the volunteer balancing energy. While the balancing energy provider's payment depends on the energy, the balancing capacity provider's payment depends on the available capacity. This can be affected by possible activation payments. (*Fingrid,* 2014)

RRs release the FRRs back in use if the demand is long-lasting. This secures the power system if multiple large-scale and long-lasting system imbalances occur simultaneously. RRs are not used in the Nordic power system. (*Fingrid,* 2014)

2.3 Imbalance Settlement

Electricity production and consumption are rarely exactly as expected, but the TSO requires a balance between them to maintain the frequency close to 50 Hz. Therefore, the TSO uses balancing power from the balancing power market, described in chapter 2.2. The balancing power market is financed by imbalance settlement fees, which are calculated after delivery. In Finland, Norway and Sweden, imbalance settlement services are provided by eSett. eSett is an Imbalance Settlement Responsible (ISR) owned equally by Fingrid, Statnett and Svenska kraftnät, the TSOs from Finland, Norway and Sweden. The operation of eSett began in May 2017. (*Fingrid,* 2014, *eSett,* 2015)

The imbalance settlement includes several participants. For each produced and consumed unit of electricity, there is always a balance responsible party (BRP). A BRP is a company with an Imbalance Settlement Agreement with eSett and a Balance Agreement with the TSO. The electricity retailer (RE), producer or consumer must act as a BRP or select one. eSett is then responsible for carrying out the imbalance settlement and invoicing BRPs for their imbalances or balancing services. The distribution system operator (DSO) is responsible to meter the production, consumption and exchange and reporting the required data to the REs, BRPs, TSP and eSett. (*eSett,* 2015)

Some additional players include the nominated electricity market operator (NEMO) and the service provider (SP). The NEMO is responsible to report power exchange trades per RE and MBA to eSett. The SP offers balance management and settlement services for the market players, such as the BRPs, REs and DSOs. (*eSett*, 2015)

There are several market entities concerning the imbalance settlement. A market balance area (MBA) is an area in which the power exchange market price is equal. A metering grid area (MGA) is an area in which consumption and / or production exchange can be measured. A production unit (PU) is a power plant with a generator or a set of generators. A regulation object (RO) represents a set of one or several generators and stations within an MBA in Finland and Sweden, or within one or several MBAs in Norway. (*eSett,* 2015)

The Nordic imbalance settlement model originates from the harmonized Nordic model carried out in 2009. It's built from two imbalances, production and consumption, that are calculated and settled. Production imbalance volume is the difference between the measured and planned production with the subtraction or addition of the production imbalance adjustment. Consumption imbalance volume is the sum of consumption, planned production and MGA imbalance with the subtraction or addition of trade and consumption imbalance adjustment. The calculations are presented in Figure 3. (*eSett,* 2015)

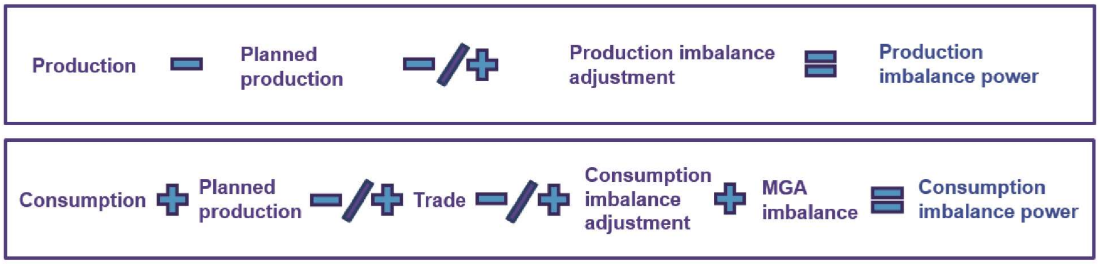

Figure 3 Production (top) and consumption (bottom) imbalance settlement volume calculation (*eSett,* 2015)

The production imbalance settlement is priced by the less favorable price of the power exchange market price and the imbalance price and is therefore called the two-price model. The consumption imbalance settlement is priced only with the imbalance price, so it is called the one-price model. (*eSett,* 2015)

Table 1 illustrates the 2-price formation in Finland. Production imbalance power sold by Fingrid to the BRP is equal to the up-regulating price. If there is no up- or down-regulation or if there is down-regulation, imbalance power is sold by the day-ahead price. Production imbalance power purchased by Fingrid from the BRP is equal to the down-regulating price. If there is no down- or up-regulation or if there is an up-regulation, the imbalance power is purchased by the day-ahead price. (*Fingrid,* 2019b)

Table 1 presents also the 1-price formation. Consumption imbalance sales power costs the same as the purchase power. The price for up-regulating hour is the up-regulating price and the price for the down-regulating hour is the down-regulating price. If there are no regulations, the price equals the day-ahead spot price. (*Fingrid,* 2019b)

	2-price			1-price			
	Up-regulating hour	No regulations	Down-regulating hour	Up-regulating hour	No regulations	Down-regulating hour	
Up-regulating price	100	50	50	100	50	50	€/MWh
Spot price	50	50	50	50	50	50	-
Down-regulating price	50	50	20	50	50	20	-
Fingrid's sales price for balance power	100	50	50	100	50	20	-
Fingrid's purchase price for balance power	50	50	20	100	50	20	-

Table 1 Pricing of imbalance settlement in Finland (*Fingrid,* 2019b)

BRP's imbalance is priced currently by hour and by using both production (2-price) and consumption (1-price) imbalances, but it will soon be priced only with the latter and for every 15 minutes. The upcoming changes are discussed in chapter 4. (*Fingrid,* 2019b)

In Finland, there is currently a fixed weekly balance service fee of 30€, actual production fee of 0,14 €/MWh, actual consumption fee of 0,22 €/MWh and a volume fee for the consumption imbalance power of 0,5 €/MWh. The fee categories are similar for Sweden and Norway, but the magnitudes are different. In Sweden, there is also a peak load reserve fee which finances the peak load reserves in the Swedish MBAs. The magnitudes may also vary within the country with one month's notice, but the goal is to have the same prices for at least one year at a time. TSOs calculate and set the fees and report them to eSett. (*eSett,* 2015, *Fingrid,* 2012)

To present an example of a production balance, if the actual production is 65 MWh and the production plan is -60 MWh, the production balance has a surplus of 5 MWh, which is sold from the BRP to the TSO. The consumption balance includes, for example, the total production of 65 MWh, the sales in the day-ahead market of -35 MWh and the actual consumption total of -45 MWh. The deviation of these is -15 MWh, which is sold from the TSO to the BRP.

Table 1 indicates the assumptions that the spot price is 50 € / MWh, the up-regulating price in the up-regulating hour is 100 €/ MWh and the down-regulating price on the down-regulating hour is 20 € / MWh. Within these circumstances, the costs for a BRP in Finland are calculated according to the Equations (1), (2), (3) and (4). Equation (2) calculates the cost of balancing power on an up-regulating hour, Equation (3) on a non-regulating hour and Equation (4) for a down-regulating hour.

Costs of balancing power:

$$- production\ balance\ surplus\ offset + consumption\ balance\ deficit\ expenditure + imbalance\ power\ volume\ fee + production\ fee + consumption\ fee = total\ expenditures \tag{1}$$

Up-regulating hour:

$$-5\ MWh \times 50 \frac{€}{MWh} + 15\ MWh \times 100 \frac{€}{MWh} + 15\ MWh \times 0.5 \frac{€}{MWh} + 65\ MWh \times 0.14 \frac{€}{MWh} + 45\ MWh \times 0.22 \frac{€}{MWh} = 1276.50\ € \tag{2}$$

No regulations:

$$-5\ MWh \times 50 \frac{€}{MW} + 15\ MWh\ \times 50 \frac{€}{MWh} + 15\ MWh \times 0.5 \frac{€}{MWh} + 65\ MWh \times 0.14 \frac{€}{MWh} + 45\ MWh \times 0.22 \frac{€}{MWh} = 526.50\ € \tag{3}$$

Down-regulating hour:

$$-5\ MWh \times 20 \frac{€}{MWh} + 15\ MWh\ \times 20 \frac{€}{MWh} + 15\ MWh \times 0.5 \frac{€}{MWh} + 65\ MWh \times 0.14 \frac{€}{MWh} + 45\ MWh \times 0.22 \frac{€}{MWh} = 226.50\ € \tag{4}$$

3 Wind Power Challenges

The share of wind power is increasing rapidly in Finland. This chapter discusses the main challenges related to wind power and some technologies that help mitigate the challenges.

3.1 Challenges for the Wind Power Producer

The national and global share of intermittent solar and wind power is increasing. Figure 4 shows the growth of wind power production in Finland. There is a clear increase over the past years. As Figure 5 indicates, in 2018, 0.2% of the produced electricity in Finland was from solar power and 9% was from wind power. Solar power has tripled from 2017 to 2018 in Finland, but the share is still minor compared to wind power. Therefore, for simplicity, this thesis focuses on the latter. This chapter discusses the challenges related to wind power from a wind power producer's perspective. (*Suomen Tuulivoimayhdistys ry,* 2019, *Findicator,* 2018, *Finnish Energy,* 2019a)

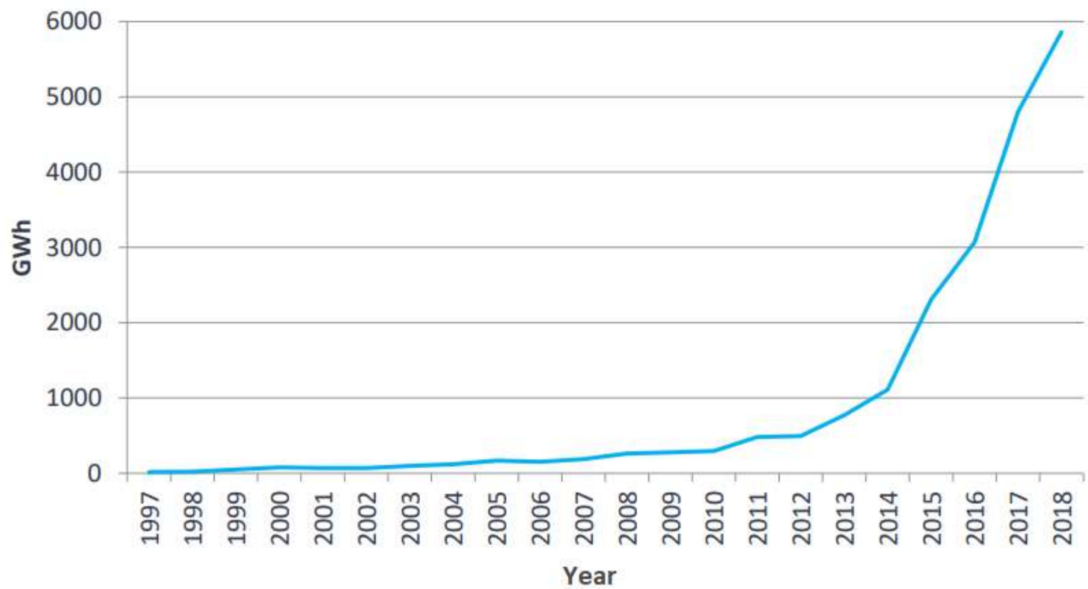

Figure 4 Annual wind power production in Finland (GWh) (*Suomen Tuulivoimayhdistys ry,* 2019)

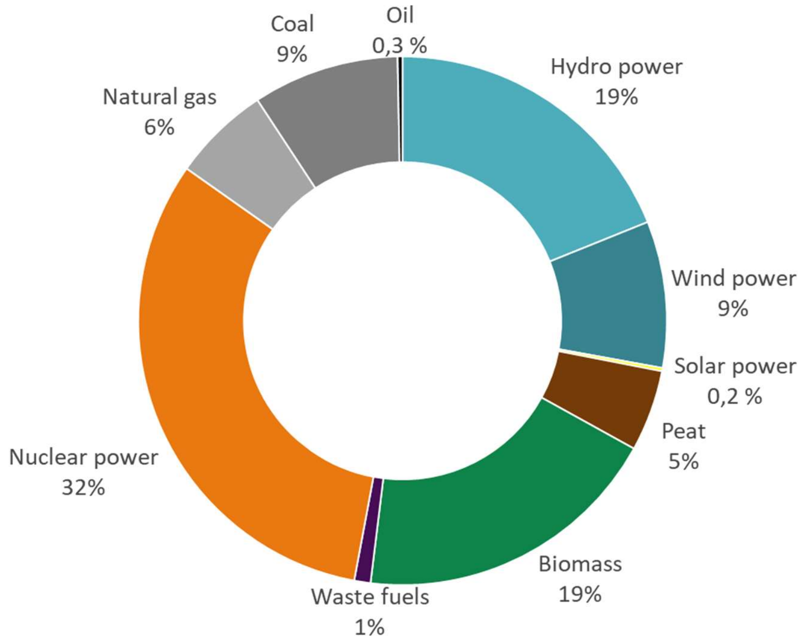

Figure 5 Electricity generation by energy source of the total 67 TWh in Finland in 2018, with a 47% share of renewables and a 79% share carbon dioxide free energy sources (*Finnish Energy,* 2019a)

3.1.1 Intermittency and Electricity Markets

Wind power is volatile. The hourly wind power production variability is illustrated in Figure 6 for several months and Figure 7 for two weeks. An important remark is that these figures illustrate average hourly production. The variation in real-time production is likely even higher.

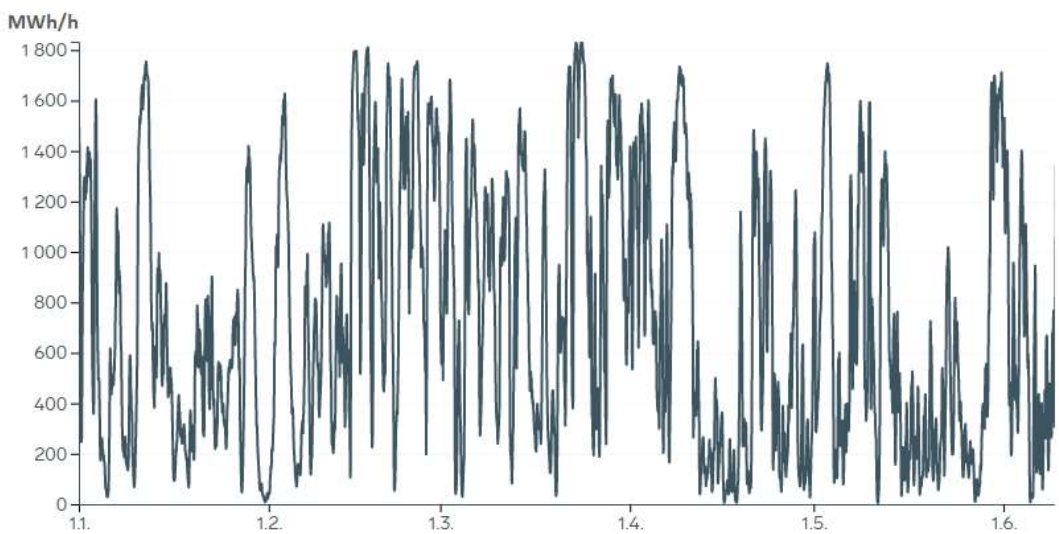

Figure 6 Hourly wind power production in Finland from January to June 2019 (*Fingrid,* 2019g)

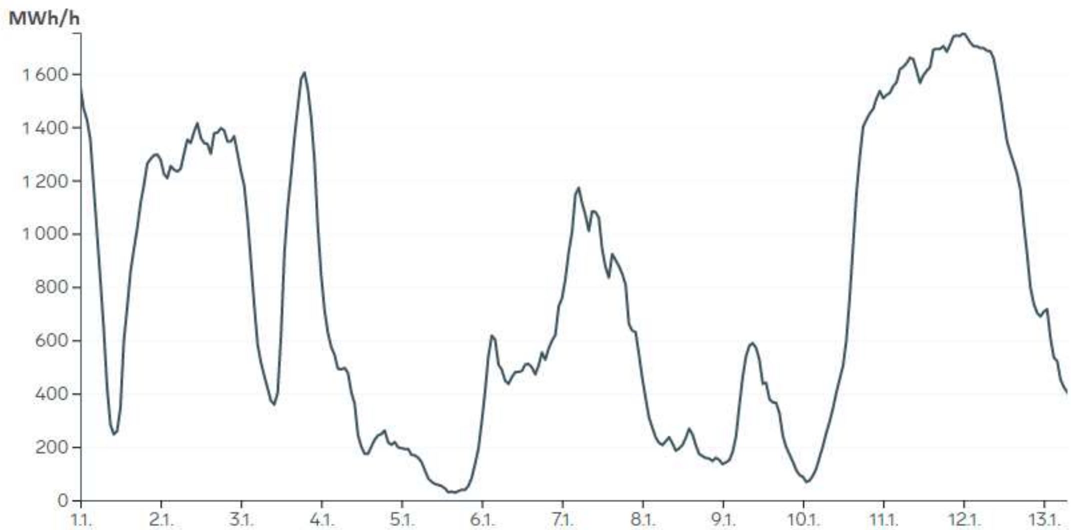

Figure 7 Hourly wind power production in Finland 1.1.-14.1.2019 (*Fingrid,* 2019g)

If wind power will increase its market share significantly, it's volatility will inevitably affect the Nordic electricity market. According to Hirth (2016), Nordic countries can somewhat cope with the intermittent wind power roughly up to a share of 20% with the help of flexible hydropower. After that, challenges may arise concerning power system balance.

Also, Kringstad (2018) found that in Norway, 10 and 20 TWh increase in wind power production would decrease the power market price, but the decrease would not be significant. With 10 TWh of new wind power, the wind-weighted price would be reduced by 3 € / MWh and with 20 TWh the reduction would be 7 €/MWh. 10 TWh would mean 6.7% and 20 TWh 13.4% of the overall production in 2017 (*Statistisk sentralbyrå,* 2018). The price decrease is slightly lower in Northern price areas in Norway. This is due to price bottlenecks in the south, which hamper the evening out of the prices. Also, the prices were lower in the North already in the first place. Another finding was that the wind-weighted price decreases somewhat faster than the average price with increasing wind power.

Despite a significant increase in intermittent renewable energy sources in Germany, there has been, against expectations, a prominent decline in the use of balancing reserves. During 2011-2017, Germany more than doubled its wind and solar power generation and decreased its use of balancing reserves by 55%. The decline in balancing energy is caused by the changes to processes, technology, market design and incentives. This suggests that substantial variable renewable energy investments can be made with low cost if processes, policies and markets are designed reasonably. (Koch and Hirth, 2018)

The correlation between average wind power output and standard deviation of wind power in Poland in 2016, 2017 and 2018 is presented in Figure 8. The hourly variations of the wind power seem to increase along with growing wind power output volumes. (Simla and Stanek, 2020)

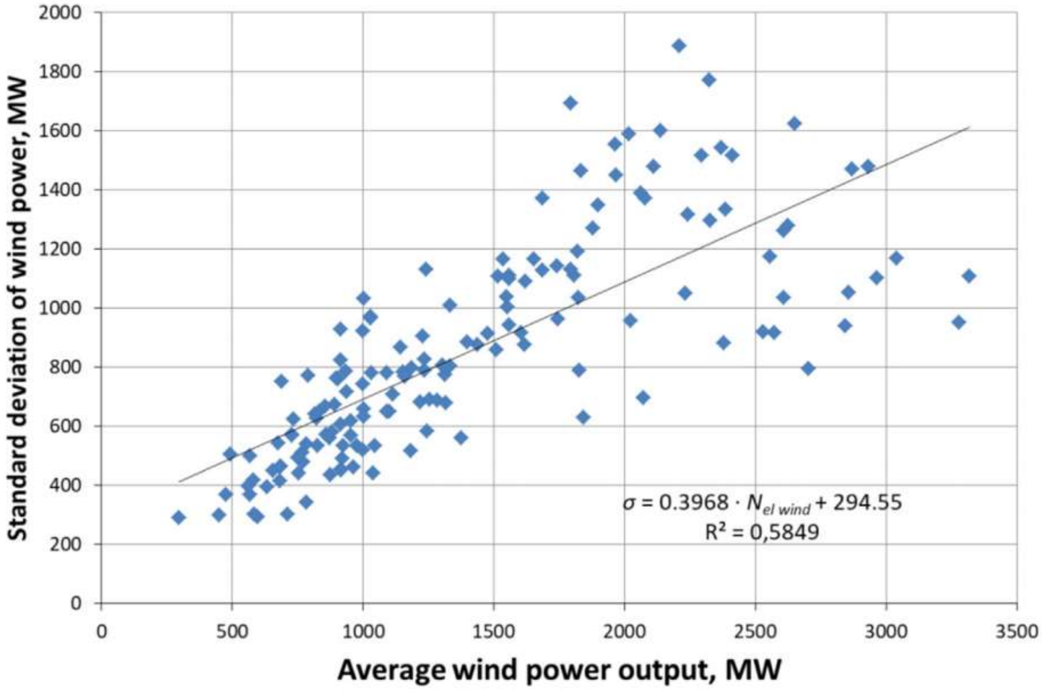

Figure 8 Correlation between the standard deviation of wind power output and the average wind power output (Simla and Stanek, 2020)

Pilpola and Lund (2019) found that wind power could be cost-effectively integrated up to a 37% share in Finland. This would require sector coupling, which means interconnecting the energy-consuming sectors with the power-producing sector. The wind power share may be increased by up to 70%, but this would cause a 60% higher system cost due to the investments in power to gas or electrical storage. Additional solutions to help with the integration include power-to-heat, smart charging of electric vehicles, vehicle-to-grid, biomass-to-biofuel, thermal storage, and wind power curtailment. Also increasing nuclear power may increase cost-effectiveness up to a limit.

3.1.2 Forecast

Wind power is not only intermittent, but also challenging to forecast. Figure 9 presents the wind power forecast and production on 20-25. February 2019. The forecast for wind power production during a specific moment has improved between the previous day and the previous hour but is still inaccurate.

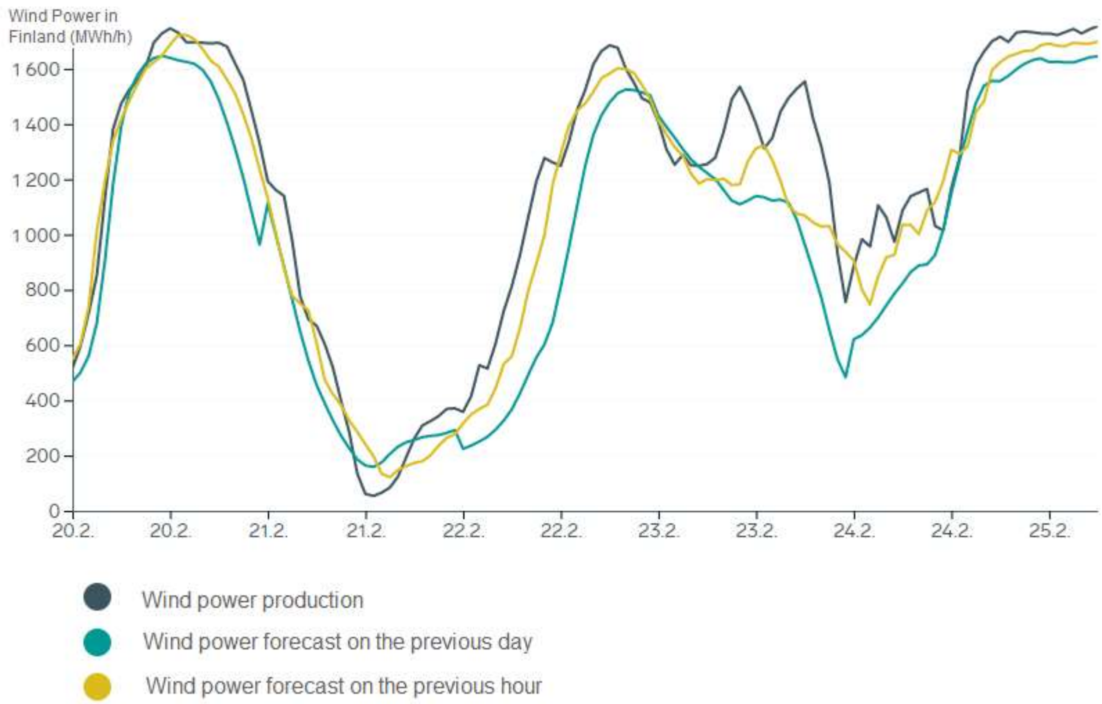

Figure 9 Wind power forecast and production on 20.-25. February 2019 in Finland. Edited from Fingrid (2019g)

Wind power forecast errors can be divided into level errors and phase errors. Level errors are related to an incorrect scale of the production and phase errors are related to incorrect timing of the production. The error types are presented in Figure 10. The level errors of wind power forecasts are based often on a poor configuration of the forecast model, but the phase errors are more challenging, often based on an incorrect timing of the weather front, resulting in larger issues. (Holttinen, Miettinen and Sillanpää, 2013)

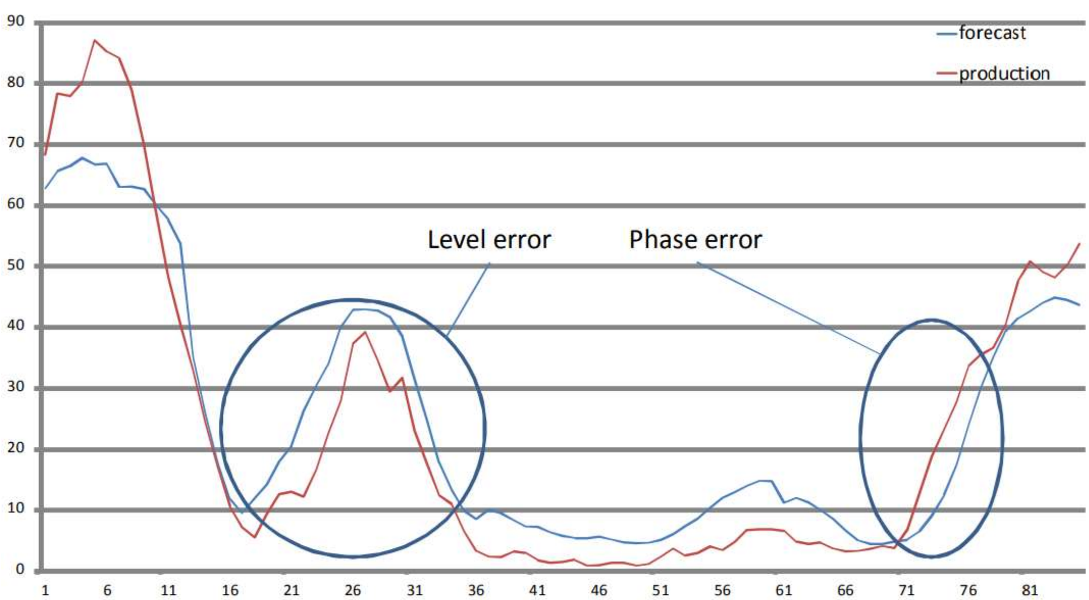

Figure 10 Wind power forecast level and phase errors (Holttinen, Miettinen and Sillanpää, 2013)

3.2 Challenges for the Power Grid

Wind power creates some challenges for the power grid. The challenges are related to power quality, which is degraded by the intermittency of wind power production and the reduction of inertia caused by wind power production.

The power system frequency is an indicator of the balance between consumption and production. In Finland, the frequency needs to stay close to 50 Hz. This level is affected by numerous factors, of which one is intermittent wind power production. Market operators are responsible to plan their production and consumption in advance, but wind power is impossible to be predicted flawlessly. High levels of wind power cause major imbalances, which result in significant frequency fluctuations which weaken the power quality. The TSO aims to guarantee a perfect balance between production and consumption. (Ochoa, Martinez, 2018, *Fingrid,* 2018c)

Another challenge related to increasing wind power is that wind power decreases the inertia of the electricity grid. Inertia means the resistance to change and inertia in the grid means kinetic energy in generators and motors at power plants and factories. These generators and motors rotate at the same frequency as the grid and therefore their mass produces inertia to the grid which slows down and decreases frequency dips and peaks. This means traditional power plants help keep the power system in balance. (Leinonen*,* 2018)

Wind and solar energy decrease inertia because they are connected to the grid without any rotating mass. Wind power plants usually include a frequency converter and thus, the kinetic energy of the rotating mass is not provided to the grid in case there is a frequency dip or peak. When inertia decreases, these sudden frequency changes act faster and larger. Additionally, imported electricity decreases inertia, if it is imported via direct current connections. (Leinonen*,* 2018)

The solution to decreasing inertia is to limit the magnitude of possible frequency changes by limiting the production of the biggest power plants and have quickly activatable reserve power. The latter is a better solution, since decreasing a power plant's production as a precaution is far worse for the grid and the market than activating reserve power only when a fault occurs. (Leinonen*,* 2018)

3.3 Technologies to Mitigate the Wind Power Challenges

To enable a large share of intermittent wind power, solutions are needed to tackle both the economic and technological challenges of wind power. This chapter presents electricity storages, energy storages as heat, demand response mechanisms, flexible power generation and the importance of the electricity market.

3.3.1 Electricity Storages

The integration of large amounts of variable renewable energy increases power system variability and thus requires solutions to keep the system in balance. In addition to demand response and flexible power generation, one solution for this is to have more electricity storages. They will likely play some role in the future's Finnish power system. (Zhao et al., 2015, Child and Breyer, 2016, Ochoa and Martinez, 2018)

Electricity may be stored in several different ways: mechanical, electrochemical, chemical, electromagnetic and thermal energy storages. Mechanical energy storages include pumped hydro storage (PHS), compressed air energy storage (CAES) and flywheel energy storage (FES). Electrochemical energy storages include the battery energy storage system (BESS). Chemical energy storages include hydrogen storage and electromagnetic storages include the supercapacitor and the superconducting magnetic energy storage (SMES). This chapter focuses on the non-thermal electricity storages, and the thermal energy storages are more thoroughly discussed in chapter 3.3.2. The different storage methods are presented in Figure 11. (Zhao et al., 2015)

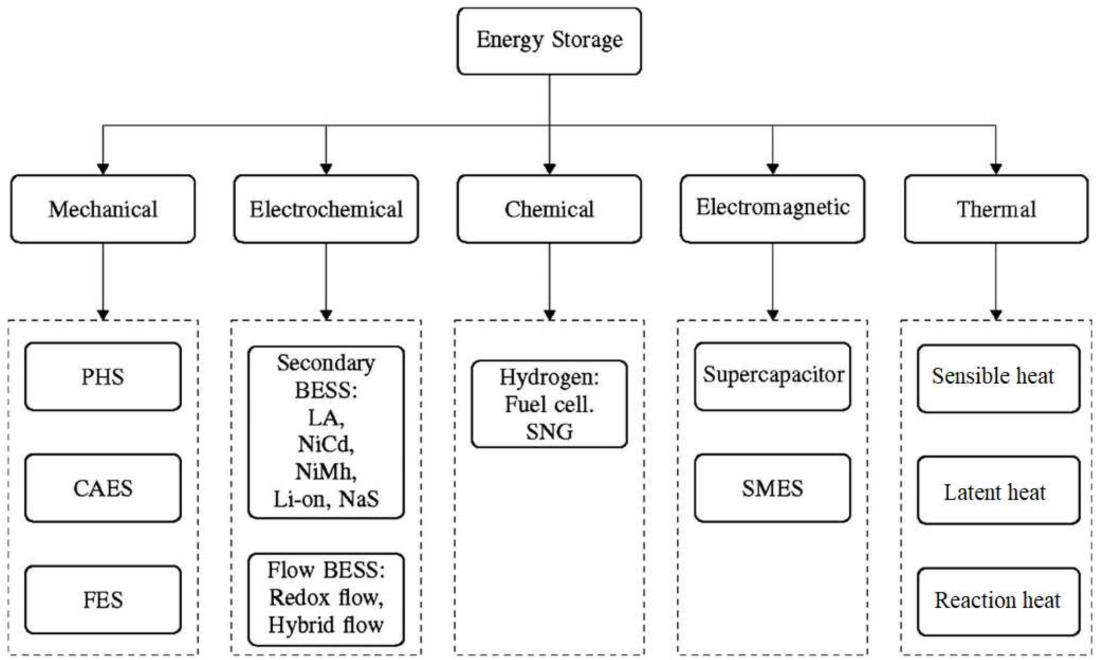

Figure 11 Energy storage options, modified from Zhao et al. (2015)

Since wind power is currently the most dominant intermittent energy source in Finland (*Finnish Energy,* 2019a), it is considered beneficial to examine energy storages from the wind power point-of-view. Some storage solutions are more plausible than others. Here a few feasible options are discussed.

A PHS uses excess electricity to pump water to store the electricity as potential energy. The storage can then be used to generate electricity when needed even in rural areas or island grids. A PHS may be a profitable addition to wind power under a reasonable discount rate. Profitability is increased via the decreasing balancing costs of wind power. This effect multiplies if the wind power share increases. (Karhinen and Huuki, 2019, Pali and Vadhera, 2018, Kapsali and Anagnostopoulos, 2017)

A CAES may be used to compress air with the excess wind power. The compressed air may be expanded to generate electricity when needed. A CAES system performs better at a variable than a constant shaft speed: the variable shaft speed mode enables to utilize more excess wind energy, store more compressed air, generate more electricity and provide longer discharging time and has a lower LCOE than at constant shaft speed. The CAES storage pressure vessel must match the wind turbine rated power output. A CAES stabilizes wind power production effectively and can provide better market conditions for it. (Jin, Liu and Li, 2019, Meng et al., 2019)

The BESS is one of the most discussed energy storage systems. Some studies find BESSs economically feasible, some studies don't. Loukatou et al. (2018) state that battery units may increase the revenue of a wind farm significantly. Major savings come from avoiding imbalance costs for unstable wind power and selling electricity in the market. Also, when there is no restriction to the state of charge, the annual revenue is higher, but this is only theoretical since limiting the state of charge extends the battery's lifetime and therefore leads to the most profitable business case. Frate et al. (2018) state that in Italy, a BESS connected to wind power is not an economically viable solution, because of the battery degradation, too high costs and too low profits.

Wind power may be converted into hydrogen, which may be stored and generated back to electricity (Zhang et al., 2019) or used for other purposes, such as injected in natural gas pipelines (Gu et al., 2019) or used in light-duty vehicles (LDVs) (Nagasawa et al., 2019, Apostolou and Enevoldsen, 2019). A power-to-hydrogen-to- power case may be more profitable and reliable for wind power than a lithium-ion battery. However, the lithium-ion battery reduces wind losses and has a smaller environmental impact compared to the hydrogen storage. (Zhang et al., 2019) Mixed in natural gas, the hydrogen would increase the combustion stability of the gas (Gu et al., 2019). What comes to fueling LDVs, it is often more economically feasible to produce hydrogen with wind power than selling the produced electricity to the day-ahead market (Nagasawa et al., 2019).

An SMES may help maintain the voltage at the point of common coupling at a preset value during wind gusts. This point is where the wind energy conversion system is connected to the SMES. The SMES also provides a fast response time for charging and discharging. (Aly et al., 2016)

Many of the discussed energy storage options may be feasible for wind power. However, for simplicity, this paper focuses on batteries, more precisely, on Lithium-ion batteries.

3.3.2 Energy Storage as Heat

As mentioned earlier, energy may be also stored as heat. Thermal energy storage methods include sensible heat, latent heat and reaction heat storages. A sensible hear storage has a storage medium, such as water, of which temperature increases when heat is added. A latent heat storage stores heat in the phase change of its storage medium, such as the change from solid to liquid. A reaction heat storage stores heat via the endothermic and exothermic reaction processes. (Burheim, 2017) As mentioned in chapter 3.3.1, the potential of storages to even out wind power production is investigated, however, instead of non-thermal energy storages, this chapter focuses on thermal storage.

There is an abundance of studies concerning sensible heat storages of wind power, but it seems challenging to find any studies regarding latent and reaction heat storage of wind power. One reason behind this is that the sensible heat storage is the most common and known technology (Kalaiselvam and Parameshwaran, 2014). Therefore, only the sensible heat storage is discussed in this chapter.

A wind-powered sensible heat storage system is competitive and even more economically feasible than a wind-powered battery storage system, when the system is used to even out electricity generation volatility (Okazaki, Shirai and Nakamura, 2015) or to heat spaces (Cao et al., 2018). The storage system becomes even more attractive when it's built close to a concentrated solar power and/or a biomass plant since then some components may be shared. When the aim is to even out wind power production, electricity may be converted to thermal energy via electromagnetic induction straight from the rotating turbine. The heat is then generated back into electricity. A wind-powered thermal system enables a flexible operation of wind power and it may even absorb electricity from the grid. (Okazaki, Shirai and Nakamura, 2015)

If the aim is to only produce heat from wind turbines, it may be produced from the via direct electrical heating or heat pumps, of which the latter is the more feasible option (Vorushylo et al., 2018). After the heat has been stored in the sensible heat storage, it may be used to heat spaces and even be fed in a district heating network (Wang et al., 2019, Cao et al., 2018).

3.3.3 Demand Response

While the share of intermittent renewable energy sources grows, also the need for demand response (DR) increases. DR is the modification of demand volumes by shifting them from one time period to another according to the market's needs. In some marketplaces, there are economic incentives for demand response. These include markets with a volatile price. Most electricity contracts hold a fixed price since they are very secure from the consumer's point of view. However, there is an increasing number of spot-market contracts. (A. Rautiainen et al., 2017)

According to International Energy Agency's Munuera and Fukui (2019), there is a huge potential for demand response to increase. Demand response increased only 4% globally in 2018, staying in the average growth rate of the previous 5 years, even though the potential for DR has been significantly increasing. In order to raise the DR growth level, new markets are needed for flexibility and ancillary services, and the already existing markets need to open new business opportunities like virtual power plants and aggregation.

Some major consumers are uncertain about taking part in demand response since shifting the consumption to another time frame might risk their profit. And when concerning small consumers, the advantages of DR must be enormous for it to be competitive against the secure fixed-price contracts. (Rautiainen et al., 2017)

However, there are several factors that increasingly encourage consumers to take part in DR. Balancing power and reserve markets offer possibilities for small consumers. Major consumers need high-quality forecast models to make sure taking part in DR is worthwhile. The upcoming common European spot market may increase the attractiveness of DR. (Rautiainen et al., 2017)

Helin (2019) states that there is a high industrial demand-side management (IDSM) potential in the pulp and paper industry in Finland. However, due to the low prices of regulating power, the current capacity is only partially feasible. IDSM also faces other significant challenges including the risk-, machinery start-up- and electricity costs.

Olkkonen (2019) mentions that demand response is most potential in the winter months in Finland when the electricity demand is highest and depends most on outdoor temperature and time of the day. There is a potential in preheating hot water storage for space heating up to 12 hours before consumption, but in reality, this might be smaller depending on the consumer's comfort preferences. The annual utilizable capacity decreases by 31% if the shifting time is decreased to six hours.

Demand response would balance residual demand in the day-ahead market. It would decrease the demand for thermal power and cross-border balancing during peak hours. Thus, it would enable even more efficient utilization of wind power during consumption off-peak hours. (Olkkonen et al., 2018) However, demand peaks would also increase with a higher share of wind power and if the uncertainty of the day-ahead demand is considered. The wind power variation may cause less optimal demand response during the day, due to the increased differences of forecasts and measures of electricity demand. Therefore, demand response is great for short-term variations in residual demand, but it's potential to even out renewable energy peaks is low due to technical and economic restrictions. Consequently, demand response may only partially replace conventional flexible electricity production. (Olkkonen, 2019)

In Finland, heating loads have a significant potential in demand response in 2030. The availability of demand response capacity varies between 80 and 5600 MW, being higher from September to April. The increased utilization of demand response may cause new demand peaks during days when residual demand variation is high. This intensifies if the share of wind power increases. Significant differences between forecasts and measurements in electricity demand may decrease the feasibility of demand-side resource capacity. (Olkkonen et al., 2018)

Olkkonen (2019) also states that increasing the demand response would require investments in energy management systems that provide an automatic reaction to balancing signals such as the market price. Possible demand response programs could be created and lead by the TSO or DSO. Using such programs might increase the efficiency of demand response. Needless to say, Nordic power markets have a cross-border exchange. Olkkonen concludes that demand response effects should not only be viewed from a national perspective but also internationally.

3.3.4 Flexible Power Generation

Increasing intermittent renewable energy sources presumably requires more flexible power generation. Currently, flexible hydropower is a major element in the Nordic power markets. Hydropower is an excellent solution to adjust the electricity production volumes quickly when needed. The share of hydropower of the overall production in Finland is annually 10-20%, depending on the water reserves. Finland also imports significant amounts of hydropower from other Nordic countries. There is some potential to increase hydropower in Finland, but the environmental restrictions reduce the potential locations to few, and the profitability of the remaining locations is uncertain. (*Energiateollisuus,* 2016) Also, because the Nordic power system is so strongly dependent on flexible hydropower, in case of severe drought, the importance of other flexible production solutions grows. (Jääskeläinen et al., 2018)

The planned new nuclear plants Olkiluoto 3 and Hanhikivi 1 and transmission lines between Finland and Sweden will be beneficial to the Nordic power system, increasing energy security, price stability and power quality (Jääskeläinen et al., 2018). Nuclear power is currently operated as baseload, but if needed, it may also be operated flexibly. However, since the fuel cost of nuclear power generation is relatively low (around 8.2 € / MWh), profits of flexible production need to be high for it to be profitable. Nuclear power flexibility would support renewables' share grow in the markets. If Finnish nuclear power plants are turned into flexible operators, supplementary safety research is required. (Loisel et al., 2018, Hyvärinen, 2014)

Another flexible production option is a conventional gas or coal power plant. Gas power plants are more feasible to flexible use than coal power plants since their start-up time is significantly shorter and ramping rates higher. Also, NO_x, CO_2 and CO emissions are approximately 50-100% higher at full load in coal plants than in gas plants. (Gonzalez-Salazar, Kirsten and Prchlik, 2018)

If wind power increases significantly on the market, CHP production may decrease. In a study carried out by Mikkola and Lund (2016), increasing wind power seems to replace more gas CHP than coal CHP. It will also increase exports significantly and decrease imports slightly.

District heating is still a major heating solution in Finland, Sweden and Denmark, covering approximately half of the overall heat supply. There is a potential for flexible district heating in the future. An additional heat storage helps optimize the operation and lower costs. (Sneum and Sandberg, 2018)

Excess wind power may be converted to heat with power-to-heat solutions. According to Salpakari, Mikkola and Lund (2016), heat pumps could decrease wind power production surplus in Helsinki, Finland, area by 35% without any storage and 37-41% with storage or load shifting. The model also resulted in having a highly positive NPV for wind power and power-to-heat combination. However, it also resulted in a negative NPV for load shifting with electric heating and commercial refrigeration if residential loads were included, due to the high investment costs in the control system. Also, wind power and power-to-heat were non-profitable, if the operation caused loss to CHP plants' production.

According to Brouwer et al. (2016), one option to handle the variability of generated power is the curtailment of the intermittent renewable power production. However, they found that this option reduces only 2 % of costs if 80 % of electricity is produced by intermittent renewable energy sources.

3.3.5 Conclusion

This chapter discussed the potential of electricity and heat storages, demand response and flexible power generation to mitigate the intermittency challenges of wind power. Many of the discussed energy storage options may be feasible in Finland, but some in particular.

There are several storage methods that seem potential for storing wind power in Finland. The potential of PHS, CAES, BESS, Hydrogen and SMES was discussed. The least-cost solution is uncertain, but the increasing demand for BESSs due to the increasing demand for electric vehicles will reduce the costs for battery modules and therefore also the costs of stationary BESSs (*IRENA*, 2017).

District heating is still a major heating method in Finland, and despite the improved energy efficiency in buildings, the district heating volumes have been increasing (*Finnish Energy,* 2019b). There seems to be a great potential in utilizing excess wind power production to produce district heat.

Demand response seems to be potential in Finland especially for heating and pulp and paper industry, which are still thriving. Since wind power production and electricity demand cannot be reliably forecasted during peak hours, demand response cannot react well to wind power variations. The market price is the best incentive to encourage using demand response. Demand response may increase in the future if the market price pushes to increase it.

What comes to the flexible producers, hydropower is and will be a dominant flexible power source in the Nordic power markets. However, there is not much potential to increase hydropower in Finland (*Finnish Energy,* 2019c). Also, conventional flexible power plants, such as coal power has been decreasing (*Statistics Finland,* 2019) and the dependency of gas on taxation brings challenges (*Finnish Tax Administration,* 2019). However, the entry of substantial amounts of intermittent renewable energies may lure new flexible power producers on the market or force some current stable producers to introduce flexibility.

In addition to the market players also the Nordic TSOs are making their move. The Nordic electricity market is shifting to encourage BRPs to be more accurately in balance. One of the main reasons behind this is to maintain high power quality. In Germany, despite the increasing variable renewable energy sources, the power system balance has improved, thanks to the implementation of the 15-minute imbalance settlement period (Koch and Hirth, 2018). The Nordic electricity markets' solutions to increasing variable renewable energy production are more thoroughly discussed in chapter 4.

4 The Reformation of the Nordic Electricity Market

Consumption and production need to be balanced. Intermittent renewable energy sources are increasing and at the same time traditional, dispatchable energy sources are decreasing. This creates both new challenges and opportunities in the electricity market. This chapter focuses on the major upcoming changes in the Finnish electricity market from an electricity retailer's or producer's perspective.

One major upcoming change is a shorter imbalance settlement period, which allows market participants to react easier to changes and the costs of imbalances can be divided more accurately between the participants causing the imbalances. It may also help enable Europe-wide cross-border intraday and balancing markets. Additionally, it may encourage new demand response and smart grid-related market opportunities to arise. (*Fingrid,* 2018e) Other major upcoming changes concerning Finland include the singe price model, automated balancing power markets, common Nordic and later European FRR markets.

4.1 15-Minute Imbalance Settlement Period

Currently, all electricity markets in Finland, including the day-ahead, intraday and balancing markets, not to mention the imbalance settlement, operate via one-hour blocks. There will be a significant reformation to this when all of the above will transform into a shorter, 15-minute time resolution. The major reason behind the 15-minute imbalance settlement period (ISP) is to enable market coupling between European countries and reduce net system imbalances despite the increasing intermittent renewable energy sources. Updating other markets, such as day-ahead and intraday markets, also to 15-minute blocks, will likely improve the market functionality.

The legislation behind this transition includes the EU commission regulation 2017/2195 of 23 November 2017, which created a guideline on electricity balancing. According to this guideline, by 18.12.2020, all TSOs must provide a 15-minute ISP in all scheduling areas and verify that all market time unit boundaries coincide with the boundaries of the ISP. However, in April 2019, the Nordic TSOs insisted to postpone the 15-minute imbalance settlement period by some years. (*Fingrid,* 2018e, *Nordic Balancing Model,* 2019)

In May 2019 the Nordic TSOs provided a Nordic balancing model (NBM) roadmap presenting schedules for both the 15-minute time resolution, containing the 15-minute ISP and the 15-minute market time unit (MTU), and the single price model. The 15-minute ISP and MTU are now scheduled to launch by the end of 2022, but the exact time frame will be clarified closer to the event. The latest allowed launch time is the year 2025. The priority is to launch the 15-minute intraday and balancing market, so the 15-minute day-ahead market will most likely be launched later. The imbalance settlement will be fully transformed to the 15-minute time frame as early as possible, regardless of the market. The single price model will probably launch before or at the same time as the 15-minute ISP and MTU. This model is discussed more in chapter 4.2. (*Fingrid,* 2018f, *Nordic Balancing Model,* 2019)

The Nordic 15-minute time resolution will enable easier integration with the European electricity markets. Balancing power will take part in the European markets by 2022. Currently, there is no plan for joint European balancing capacity markets. The joint European balancing power market is more thoroughly discussed in chapter 4.4. (*Fingrid,* 2018e)

The 15-minute time resolution will challenge market participants' information systems and energy measurements. The information systems are required to handle 15-minute measurement data. The new time resolution won't affect small consumers directly. At some point, their energy measurement resolution will shift from an hour to 15 minutes. There will also likely be new products and services on the market for small consumers to utilize. (*Fingrid,* 2018e)

4.1.1 Germany

The German day-ahead and intraday markets are provided by the European Power Exchange (EPEX SPOT) and the financial markets are provided by the European Energy Exchange (EEX). EPEX SPOT provides a trading platform also for France, the United Kingdom, the Netherlands, Belgium, Austria, Switzerland and Luxembourg. EEX provides futures also for France, Austria, Belgium and the Netherlands. (Frontier Economics, 2016)

In Germany, the TSOs are responsible for keeping the power system in balance and therefore they acquire balancing power. Germany has four TSOs: 50Hertz, Amprion, TenneT and TransnetBW. The necessary balancing amount depends on the balancing energy quality and calculations from probabilistic models. (Müsgens, Ockenfels and Peek, 2014, *Netztransparenz,* 2014)

Germany already introduced 15-minute intraday auction contracts in December 2014 and 15-minute intraday continuous contracts and a 15-minute imbalance settlement period already in December 2011. The country has still an hourly day-ahead market and an hourly and a 30-minute intraday continuous market. (*Epexspot,* 2013, *Epexspot*, 2014)

The 15-minute periods have become increasingly popular, which has significantly reduced predictable imbalances, caused for instance by solar power or from electricity consumption. The increase in intraday trading volumes is presented in Figure 12. The yearly trading volume has multiplied between 2012-17. The reduction of predictable imbalances has been 80% during 2011-17. This has resulted in reductions in balancing reserve capacity and use. The balance improvement of the system is presented in Figure 13. (Koch and Hirth, 2018)

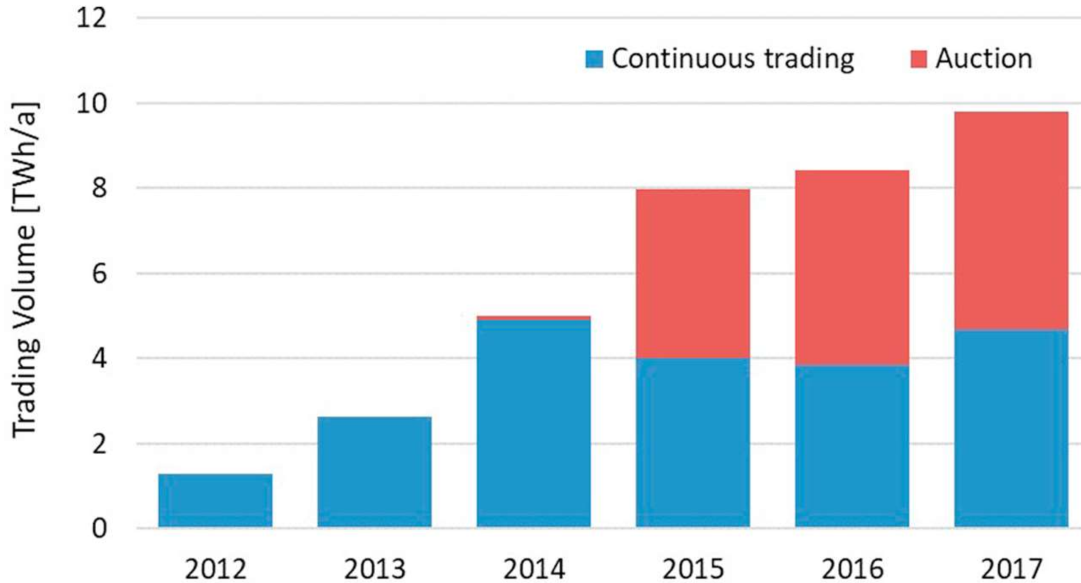

Figure 12 The yearly trading volume on the 15-minute intraday auction and continuous markets in Germany (Koch and Hirth, 2018)

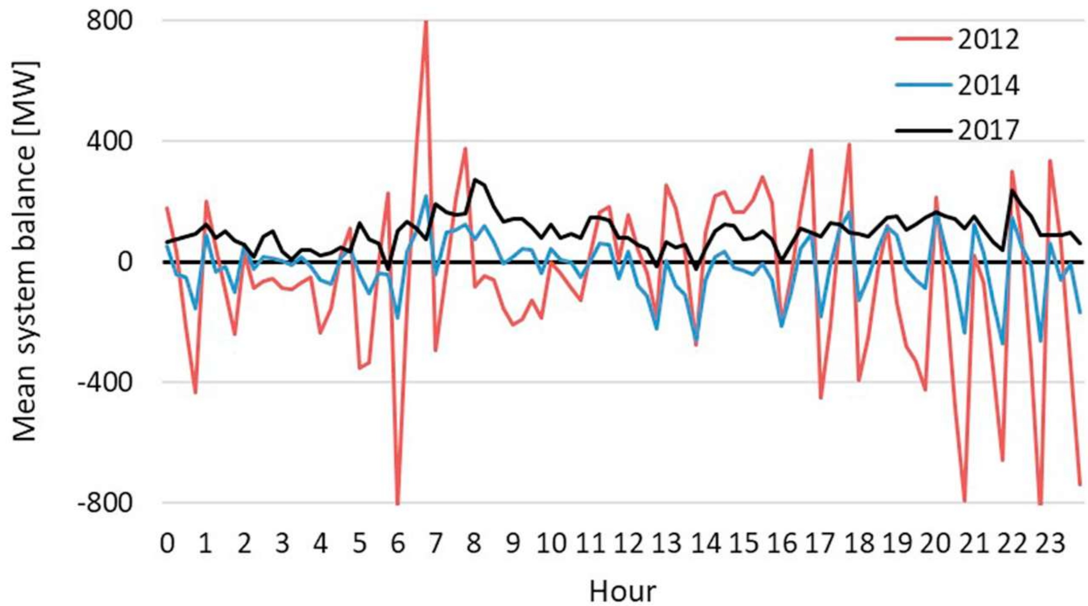

Figure 13 The mean system balance per quarter-hour in Germany in 2012, 2014 and 2017 (Koch and Hirth, 2018)

The imbalance settlement prices in Germany include one single price for every 15 minutes. Therefore, there are no differences in negative and positive balancing derivation prices. The prices are public online on the TSO's website for all participants. (*Frontier Economics*, 2016)

4.2 Single Price Imbalance Settlement Model

Chapter 2.3 presented the current imbalance settlement model with the production (2-price) and consumption (1-price) imbalance settlement model. However, soon only a 1-price model will be used. The exact implementation is still unsure. The EU commission regulation 2017/2195, which established the guideline for a 15-minute imbalance settlement period presented in chapter 4.1, advises the European Union members to primarily use a 1-price model. The 1-price model needs to be in use 18 months after the officials have accepted the TSOs' proposal of harmonizing imbalance settlement in Europe. (*Fingrid,* 2019f)

Despite the reformation, TSOs will be allowed to use the 2-price model in some scenarios. This means that the sales and purchase price of balancing power can sometimes differ. This scenario could exist in an imbalance settlement period in which there is both up- and down-regulation. (*Fingrid,* 2019f)

The 1-price model increases the profitability of reacting to the imbalances. With an equal price for the TSO's imbalance power sales and purchase, it is more expensive for the BRP to buy balancing power in an up-regulating hour and there is less profit for the BRP to sell balancing power in a down-regulating hour. (*Fingrid,* 2019b)

The 1-price model together with the 15-minute imbalance settlement period enables harmonized European electricity markets and helps the imbalance fees to correspond to the real-time regulating energy value. The latter encourages BRPs to stay in balance and take part in balancing the electricity system. This, in turn, aids the electricity production and consumption to stay in balance even if the intermittent renewable energy sources will further increase. (*Fingrid,* 2019f)

From a wind power producer's perspective, the implementation of the 1-price model will likely decrease profitability significantly, due to the challenges in forecasting wind power production and increasing balancing costs. This paper further investigates the future profitability of wind power.

4.3 Nordic aFRR and mFRR Markets and Balancing Power within aFRR

The Nordic TSOs are moving towards a common Nordic aFRR and mFRR capacity market. The Nordic aFRR market is scheduled to begin in the beginning of 2020. The preliminary timeline for the Nordic mFRR market is to launch somewhere mid-2021. This timeline will be updated. (*Nordic Balancing Model,* 2019)

As soon as the Nordic countries introduce the 15-minute imbalance settlement period, the time frame is significantly shorter than before and thus imposes an increased demand for automatic frequency restoration reserves. Hence, it's important to have a well-functioning and effective aFRR market in the Nordic countries. A functional cross-border aFRR market brings socio-economic benefits for the Nordic countries' markets. (*Nordic Balancing Model,* 2019)

While the demand for automation increases, the mFRR balancing process needs to be redesigned and it's subprocesses need to be automated. Today the TSO manually sets the demand for mFRR in the Nordics. In future, the demand will be set according to the bidding zone, based on forecasted imbalances. Therefore, the TSOs may use a central optimization algorithm for the bid selection. The algorithm uses the mFRR demand per bidding zone, the available bids and the transmission capacity between the bidding zones. (*Nordic Balancing Model,* 2019)

Most mFRRs will be enabled in a scheduled mFRR activation process, in which the TSO request, the optimization and the BSP activation are coordinated. The BSPs are activated for a time period of full 15-minutes. The scheduled activation will be used in the early phase of Nordic optimization. The mFRRs can also be activated via direct activation, in which the TSOs can also place an order for mFRRs also in between the scheduled periods. The direct activation will not be primarily used in the beginning of the Nordic balancing markets. It will be manually ordered by the TSO when direct activation is necessary. (*Nordic Balancing Model,* 2019)

Today, the aFRR market is determined by the Nordic demand for aFRR, which is based on frequency deviation. All BSPs are activated in parallel. Soon the Nordic TSOs will introduce an aFRR energy activation market, in which the aFRRs are activated in order based on energy bids. This model is similar to the current mFRR activation model. (*Nordic Balancing Model,* 2019)

4.4 Common European FRR Market

The EU commission regulation 2017/2195 guides Europe to introduce common balancing power marketplaces for mFRR and aFRR by 2022. The common European marketplaces will replace the current Nordic marketplaces. (*Fingrid,* 2019a)

The Fusion of Nordic markets with other European markets will change the product specifications. At the moment, it seems that the mFRR needs to be fully activated in 12.5 minutes and the aFRR in 5 minutes. The 15-minute imbalance settlement period needs to be introduced by then. The smallest possible offer size is 1 MW and the step size is 1 MW. (*Fingrid,* 2019a)

The European marketplace is called MARI for mFRR and PICASSO for aFRR. MARI (Manually Activated Reserves Initiative) has 25 member TSOs. PICASSO (the Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation) has 16 member TSOs. (*ENTSO-E,* 2017, *ENTSO-E,* 2018)

After the fusion, the local TSOs will continue to act as an interface for balancing market participants. In Finland, this means in practice that Fingrid keeps on handling offers and activation requests. (*Fingrid,* 2019a)

5 Methods and Data

This chapter describes the scope, methods, data and tools used in the study. All calculations were computed using Microsoft Excel and Visual Basic for Applications.

5.1 The Effects of the New Market Environment

The goal of this study is to estimate the effects of the future 15-minute imbalance settlement period and the increase of intermittent renewable energy sources in Finland from a wind power producer’s perspective. The study was carried out by analysing historical electricity market data in Finland and Germany and wind power production and forecast data in Finland.

5.1.1 The Effects of 15-Minute Imbalance Settlement Period

The transition to the 15-minute intraday, balancing power and imbalance settlement period will inevitably affect the electricity market. The goal of this section is to estimate how the transition will affect the future Finnish electricity market price by using historical day-ahead, intraday and balancing power market data from Finland and Germany. The scope is limited to the wind power producer’s perspective, and thus, only the effect on the market price is analysed.

The hypothesis of this study is that the 15-minute imbalance settlement period will probably increase the volatility of some market prices and therefore target balancing costs to those who are responsible for imbalances.

The data presented in Table 2 includes the prices and volumes of 2018, 2017 and 2016 day-ahead, intraday and balancing power markets. All Finnish market data has a one-hour market time period. The German market data includes one-hour, 30-minute and 15-minute market time periods.

Market:	**Market time period:**	**Finland:**	**Germany:**
Day-ahead	1 hour	(*Nord Pool,* 2019a)	(*Epexspot,* 2019b)
Intraday Continuous	1 hour	(*Nord Pool,* 2019b)	(*Epexspot,* 2019a)
Intraday Continuous	30 minutes	-	(*Epexspot,* 2019a)
Intraday Continuous	15 minutes	-	(*Epexspot,* 2019a)
Intraday Auction	15 minutes	-	(*Epexspot,* 2019c)
Balancing	1 hour	(*Nord Pool,* 2019a)	-
Balancing	15 minutes	-	(*SMARD,* 2019)

Table 2 The data and their sources used in the study estimating the effects of the future 15-minute imbalance settlement period in Finland

Several analyzation methods are used. The volatility is calculated by calculating the standard deviation and average of all the market prices and volumes in 2018 and dividing each standard deviation by their corresponding average. These resulting numbers are called coefficients of variation, or relative standard deviations, which represent the volatilities of each market. The volatility between the 15-minute market and the 1-hour market is estimated by comparing the volatility of the German 15-minute and the Finnish 1-hour intraday and balancing power data.

Standard deviation is used because it is a great tool to measure the dispersion of data. It is used rather than its square, variance, because since variance is expressed in square units, its scale is higher than the one of the original data set. Therefore, standard deviation describes more realistically how much the values differ from their mean. Nonetheless, it is important to note that Germany and Finland have different electricity market environments and therefore this method does not give a fully reliable result in this study.

The second study method is the analysis of an average 2018 day in the German day-ahead, intraday continuous and balancing markets. Yearly average market prices and volumes are examined for every 15-minute period of the day. This method is used to visualize how the volatility acts through time: what time of the day the dips and peaks are usually located, and how can the markets possibly affect each other. The method is eminent because one day is a very repetitive figure of human behaviour and thus also of electricity consumption. Examining the average of 365 days, the effect of exceptional or seasonal values is minimized, and the usual figure is displayed. There can be some hourly, daily, seasonal or yearly variations, and therefore the yearly averages minimize the effect of the finer time variations within the year. Intraday continuous is chosen over intraday auction, because there is only an intraday continuous market in Finland, and thus it is more relevant when analysing the Finnish markets.

5.1.2 Variable Renewable Energy Sources

The production of variable renewable energy sources, especially wind power, is rapidly increasing in Finland (*Suomen Tuulivoimayhdistys ry,* 2019). Wind power is an intermittent energy source, which means its production varies randomly and there is no clear daily shape such as the shape solar power has (*Fingrid,* 2019g). Cannibalism of wind power means that excess wind power on the market leads to a price reduction. In Denmark, the increasing of variable renewable energy has decreased the day-ahead price (Sorknæs et al., 2019). The goal of this study is to investigate how the intermittent wind power affects the day-ahead, intraday and balancing power markets in Finland, and to estimate the effect on the market value of wind power, if there was significantly more wind power in the power system. The scope is limited to the wind power producer's perspective, and therefore only the effects on the market prices and imbalance costs are investigated.

The hypothesis of this study is that there is some relation between wind power production and the day-ahead, intraday and balancing power market prices in Finland and that the increasing wind power may decrease wind power's market value.

The data of this study includes hourly and 3-minute wind power production and hourly wind power forecasts from the previous day in Finland in 2017, 2018 and the first half of 2019 (*Fingrid,* 2019c). Also, the day-ahead prices and volumes of 2017 and 2018 (*Nord Pool,* 2019a), intraday prices and volumes of 2018 (*Nord Pool,* 2019b) and balancing power prices, volumes and up/down-regulation data of 2017 and 2018 (*Nord Pool,* 2019a) is utilized. Also, the production data of some Ilmatar wind power plants in winter 2018-2019 and summer 2019 (Hakola, 2019) is utilized.

The main analyzation method used is the Microsoft Excel's correlation -function, which calculates the correlation coefficient (R) between two data sets. The correlation of several Finnish data is examined: National wind power production and intraday or balancing energy markets, national wind power forecast error and intraday or balancing energy markets, national wind power production and Ilmatar wind farms' production, and national wind power forecast and the day-ahead price.

Each correlation (R) is then squared (R-squared) to find out the coefficient of determination (R^2). This value represents "the percent of the variation in one variable explained by the other variable or the percent of variation shared between the two variables" (Ratner, 2017). The coefficient of determination is used because it helps find out how much the values of one data set explain the values of the other data set.

Finally, some calculations were made to help understand the behaviour behind wind power forecasts. The distribution of regulating hours among wind power forecast errors in 2018 and an average day for wind power production and forecast error in 2017 and 2018 is presented. Also, the standard error and standard deviation of each hour of the day is presented.

5.2 The Profitability of Different Market Scenarios

This section investigates the profitability of wind power and electrical energy storages, together and separately, in the current and future electricity markets in Finland. Major revenues and expenses are accounted for and the most economically feasible option is discovered.

5.2.1 Onshore Wind Power

The goal of this study is to compare wind power profitability via different contracts. One contract is the Power Purchase Agreement (PPA), which sets a constant price for the electricity for a fixed time period. Another contract is operating as merchant, which means the electricity price may vary. This study estimates the profitability of both methods, accounting for the current costs of balancing. A tentative estimate of the future scenario is evaluated qualitatively.

The data used in this study includes hourly Finnish wind power forecast and true production of 2017 and 2018 in Finland (*Fingrid,* 2019c) and in three Finnish wind turbines (Hakola, 2019). Also, the Finnish day-ahead and balancing power market prices and volumes of 2017-2019 (*Nord Pool,* 2019a) are utilized.

The first study calculates the correlation of the hourly average wind power production in Finland and in three independent wind turbines with the day-ahead price and buy and sell volumes between 26 November 2018 – 16 January 2019. The scope is to find out, is day-ahead a good market for selling wind power. If there is a significant negative correlation, the day-ahead market is not an optimal place for a wind power producer.

The second study calculates the revenues and expenses for an example wind power plant in 2018 and 2017. The revenues come from the hourly spot market and the expenses from the hourly balancing power market. Because all produced electricity is expected to be sold in the spot market and there is no consumption, the imbalance volume calculation gives roughly the same result now and after the implementation of the currently planned single price imbalance settlement model, which may still change (Seppälä, 2019). For example, if the production is 60 MWh, the plan is 55 MWh which equals sell to the spot market and the consumption and purchase of power is 0 MWh, there is a 5 MWh surplus both on the old and new model. In this case, the imbalance fees for the hour can be calculated as Equation 5 indicates. The imbalance pricing model itself will change after the implementation of the single price imbalance settlement model.

Imbalance fees for a BRP with no consumption or purchase of power:

$$5\ MWh \times [IMBALANCE\ PRICE]\frac{€}{MWh} + 60\ MWh \times 0.14\frac{€}{MWh} = X\ € \qquad (5)$$

The imbalance price mentioned in **Error! Reference source not found.** depends on the type of regulating hour: up-, down- or no regulation hour. The highest price is the TSO:s sale price on an up-regulating hour, and the lowest price is the TSO:s purchase price on a down-regulating hour. Other prices are equal with the spot-price. This will change, since the TSO:s purchase and sale prices will likely be equal when the single price imbalance settlement model is implemented. A weekly balancing service fee of 30 euros will be kept separately and added to the expenses at the very end of the calculations. (*Fingrid,* 2019f)

The imbalance fees are calculated hourly for the full years 2018 and 2017. The fees are first calculated using Finland's total wind forecasts and forecast errors of each hour. Then the fees are multiplied by the ratio of a single wind turbine yearly production, producing presumably 800 kWh/h on average, and the Finnish average national wind power production of the year, 472 MWh/h in 2017 and 611 MWh/h in 2018. This is a relatively rough method since the wind forecast and true production profiles of the whole country are likely different from independent wind turbines. This also gives us an estimate only from the current situation, not from the future, with the 15-minute imbalance settlement period. However, this is the best method that may be carried out with the currently available data. The effects of the 15-minute imbalance settlement period are estimated qualitatively based on the results of the previous studies in this thesis.

5.2.2 Electricity Storages

The goal of this study is to estimate the profitability of battery energy storage systems (BESSs) on the electricity market in Finland. For simplicity, the lithium-ion battery storage is selected, because it is one of the cheapest and most common battery storages (*Lazard,* 2018). The battery technical data is from IRENA (2017).

The profitability is estimated on FCR-N and balancing markets. These markets are selected because they have both up- and downregulation and the price level is relatively high. (*Fingrid,* 2018b) The day-night arbitrage of the spot markets is not selected, because it is significantly less economically attractive than the reserve and balancing markets (Zakeri and Syri, 2015). At some point, there may be also FCR-D down-regulation, but due to uncertainty and simplicity, it is excluded from this study. However, the need for this renovation will be more thoroughly investigated as late as in 2020-2021 (*Fingrid,* 2018d). The data of the FCR-N markets are from Fingrid (2019c), and the data from balancing markets are from Nord Pool (2019a).

This study includes several steps. First, the yearly price distribution of both markets, FCR-N and balancing, is visualized to tentatively estimate the profitability of these markets. Next, the profit calculations of an electricity storage on both markets are performed. Last, the profitability of electricity storage on the FCR-N and balancing markets is analysed.

The profitability of a lithium-ion battery is estimated by calculating the cost of storage that results in a positive net present value (NPV) on the FCR-N or balancing power market. A positive NPV represents a profitable investment. The calculation assumes that the markets act continuously as they did during the examined period 2017 or 2018. The calculation is based on a 15-year battery calendar life because, according to IRENA (2017), the average battery calendar life of a lithium-ion battery was 12-15 years in 2016. IRENA (2017) defines battery costs per MWh of storage capacity and, to create comparable results, the same is done in this thesis. The cost of storage includes all investment, operations and maintenance costs.

A Lithium-Ion Battery on the FCR-N Markets

The first market selected for calculations is the FCR-N market. The FCR-N market is divided into two markets: yearly and hourly markets. The hourly market does not require a yearly agreement. The hourly markets are selected because the price level of the hourly markets is significantly higher than the yearly markets. Between 2011-2019, the yearly market prices vary somewhere between 10-17 €/MWh, and the yearly averages of the hourly market prices vary somewhere between 15-38 €/MWh. The latter values are presented in Table 3. The bids of the hourly market need to be submitted by 6.30 pm (EET) on the previous day. The payment varies for each hour and is defined by the most expensive bid of the hour. (*Fingrid,* 2018b)

	Price Min. (€/MWh)	Price Avg. (€/MWh)	Price Max. (€/MWh)	Vol. Min. (MW)	Vol. Avg. (MW)	Vol. Max. (MW)
2011	0	14.94	770	0	2	58
2012	0	30.41	560	0	7	51
2013	0	36.33	514	0	10	64
2014	0	31.93	520	0	15	86
2015	0	22.32	500	0	14	75
2016	0	16.87	104.2	0	10	57
2017	0	20.87	112.7	0	34	114
2018	0	22.79	350	0	35	105
Jan-Aug 2019	0	25.28	500	0	37	112

Table 3 The annual minimum, average and maximum prices and transaction volumes on the hourly FCR-N market 2011-2019 (*Fingrid,* 2018b)

At first sight, there is at least one challenge related to the FCR-N from an electricity producer point-of-view, and it is the low average volumes. This means there is a high risk of cannibalization on the market. (*Fingrid,* 2018b)

There are some limitations that affect the choice of simulation models. The minimum size of the FCR-N is 0.1 MW. It has a dead band of ±0.05 Hz, which means, it needs to react when there is a ±0.05 Hz difference from the optimal 50 Hz frequency, but it may react already during a smaller deviation (*Fingrid,* 2018b, Tikka*,* 2014). The limit will decrease 1.1.2020 down to ±0.01 Hz which means the reserves need to react at smaller deviations. According to Huvilinna (2015), only the reaction to ±0.05 Hz should be chosen to minimize the cycles to preserve the battery durability and hence also profitability. Because the dead band is going to be decreased down to 50±0.01 Hz beginning from 2020 (*Fingrid,* 2018d), this study will investigate the charging and discharging at 50±0.01 Hz.

Since the frequency data plays a key role in the calculations, it is notable to mention that there are some significant drawbacks in the frequency data of 2017 and 2018 (*Fingrid,* 2019c). First of all, the data should present frequency values every 3 minutes. This creates a challenge when the battery has the capacity to be charged or discharged for only less than 3 minutes, let's say for example 2 minutes 40 seconds. These calculations do not know the frequency between the 3-minute values and therefore if the battery does not have the capacity to be charged or discharged during the full 3-minute time section, it is set to do nothing at all in the calculations. This results in less profit and more penalties in the calculations compared to a real-life situation. One solution would be splitting the data into smaller sections than 3-minutes and selecting the frequency data in between by interpolating, but this would require great processing power from the computer, which is not currently available for this research.

Another major issue related to the frequency data is that there are 175200 3-minute sections within one year, but the 2018 data presents 175091 values and the 2017 data presents only 154746 values. The reason behind this is that during 18 May 2017 – 29 August 2017 there was only 5-minute data. This affects the results. The effect is probably a reduction in the NPV calculations since the profitability of a storage is greatly dependent on a frequent swap between the up- and downregulation. The NPV would likely be reduced also because of the same issue mentioned previously: if the battery is able to respond for 4 minutes 30 seconds, but the data has a 5-minute interval, the battery could not be charged or discharged, no profit is made but penalties are paid for the full 5 minutes instead of the true 30 seconds. This effect would result in the reality being significantly brighter than what the calculations indicate.

For simplicity, the battery is set to be on the FCR-N market 24/7, which is different from the reality, in which offers are submitted for selected hours on the previous evening, based on forecasts and estimates on the reserve's availability. Therefore, in reality, the storage would likely have fewer hours when it's unable to respond to the FCR-N demand, and therefore it would likely be more profitable.

A Lithium-Ion Battery on the Balancing Markets

The second and last market selected is the balancing power market. The balancing market prices, both upper- and lower balancing, are based on the Nordic balancing energy markets. Balancing energy bids are given to resources of a minimum of 10 MW change in power in 15 minutes, or a 5 MW change if an electronic activation is utilized. The bids need to be submitted 45 minutes before the hour of delivery at the latest. (*Fingrid,* 2018a)

Both upper- and lower balancing energy price is set for each hour. The upper balancing is when a reserve receives payment for providing energy, and the lower balancing is when a reserve pays to reduce energy. The upper balancing energy price is defined by the most expensive upper balancing bid used, but at least the spot price. The lower balancing energy price is defined by the cheapest upper balancing energy bid used, but no more than the spot price. (*Fingrid,* 2018a)

	Vol. Min. Up (MW)	Vol. Avg. Up (MW)	Vol. Max. Up (MW)	Vol. Min. Down (MW)	Vol. Avg. Down (MW)	Vol. Max. Down (MW)
2011	0	10	630	-640	-28	0
2012	0	16	767	-356	-19	0
2013	0	14	721	-461	-18	0
2014	0	16	502	-409	-20	0
2015	0	14	435	-458	-23	0
2016	0	13	445	-330	-20	0
2017	0	17	420	-443	-23	0
2018	0	14	818	-405	-19	0
Jan-Aug 2019	0	15	472	-387	-23	0

Table 4 The annual minimum, average and maximum up- and down regulating volumes on the hourly balancing market 2011-2019 (*Fingrid,* 2018b)

	Price Min. Up (€/MWh)	Price Avg. Up (€/MWh)	Price Max. Up (€/MWh)	Price Min. Down (€/MWh)	Price Avg. Down (€/MWh)	Price Max. Down (€/MWh)
2011	0.36	53.85	1000	-20	44.36	150.05
2012	3.92	46.31	2000	-8.1	31.65	300.01
2013	1.38	45.35	2000	-66.89	37.08	210.01
2014	4.23	39.74	500	-1.07	32.19	200.05
2015	0.32	35.6	2000	-5	24.48	150.03
2016	4.04	36.87	3000	-25.55	28.18	200.09
2017	4.05	37.27	699	-1000	29.09	130.05
2018	1.59	51.78	2999	-1000	42.66	249.97
Jan-Aug 2019	0.12	50.15	3000	-19.42	39.63	199.91

Table 5 The annual minimum, average and maximum up- and down regulating prices on the hourly balancing market 2011-2019. The darker the colour, the more profitable it is to the reserve responsible (*Fingrid*, 2018b)

The annual balancing energy market minimum, average and maximum prices and volumes in 2011-2019 are presented in Table 4 and Table 5. There is some variation in the volumes and prices, but the average up-regulation price seems to be usually around 5 €/MWh higher and the down-regulating price 5 €/MWh lower than the yearly spot market price. The years 2011 and 2018 were the most profitable years for a balance provider.

The Properties of a Lithium-Ion Storage

The costs, properties and selection of BESS are based on IRENA (2017). First, the type of Li-ion battery is tentatively selected. A constantly charging or discharging electricity storage needs to have a high cycle life. The lithium iron phosphate, nickel cobalt aluminium, nickel manganese cobalt and lithium manganese oxide storages have a calendar life of around 12 years, and a cycle life of around 1 000 – 2 500. This means they would stand only around 0.23-0.57 full charge cycles on average per day during those 12 years. The lithium titanate (LTO) battery has a calendar life of 15 years and a cycle life at 5 000 at the worst, 20 000 at the best and 10 000 as a reference value. This means the LTO battery has the capability to have around 0.91-3.65 full charge cycles per day during those 15 years, having a reference value of around 1.83 full cycles per day. (*IRENA*, 2017)

According to Lazard (2018), the cost of an average lithium-ion storage varies somewhere between USD 390/kWh - USD 540/kWh, if the power-to-energy ratio of the utility-scale storage is 1:4. According to IRENA (2017), the cost of LTO varies between USD 473/kWh – USD 1260/kWh while the cost of other lithium-ion storages varies around USD 200/kWh – USD 840/kWh. Despite the costs, the LTO is selected due to its high cycle life. The depth of discharge of the LTO batteries is around 95% and for other lithium-ion batteries around 90%. The energy density for LTO and most other lithium-ion batteries is around 200-620 Wh/L. These numbers are from 2016, and IRENA forecasted that the cycle life will almost double by 2030, and the calendar life will increase to 23 years for LTO and 18 years for other lithium-ion storages. The depth of discharge and the energy density will likely stay the same. (*IRENA*, 2017)

5.2.3 Wind Power with Electricity Storages

The goal of this study is to estimate the profitability of battery energy storage systems (BESSs) paired with wind power on the electricity market in Finland. The study is made from an independent wind power producer's perspective based on today's balancing market prices. The future profitability is then estimated based on results from previous parts of this paper.

According to Lazard (2018), the levelized cost of storage (LCOS) of utility-scale lithium-ion storages is the lowest and most attractive of all BESS types and uses. Therefore, for simplicity, this study focuses on lithium-ion electricity storages.

The data used in this study is from several sources. All market data is from Finland and all data is from November 26, 2018 to January 16, 2019 and May 28 to August 15, 2019. The national wind power production forecast of the previous day, true wind power production in Finland, power system frequency and FCR-N prices are from Fingrid (2019c). The production data is from a wind farm in Finland (Hakola, 2019). The imbalance prices are from Nord Pool (2019a), and the battery properties are again from IRENA (2017).

This study estimates the profitability of a combination of wind power and a lithium-ion battery by calculating the cost of storage that results in a positive NPV in the FCR-N market if excess wind power is charged to the battery. A positive NPV represents a profitable investment. IRENA (2017) defines battery costs per MWh of storage capacity and, to create comparable results, the same is done in this thesis. The cost of storage includes all investment, operations and maintenance costs. The calculation assumes that the market acts continuously as it did during the examined period November 26, 2018 to January 16, 2019 or May 28 to August 15, 2019. The calculation is based on a 15-year battery calendar life because, according to IRENA (2017), the average battery calendar life of a lithium-ion battery was 12-15 years in 2016. The study takes into account the loss of wind power imbalance profits.

In the previous study, where a storage was on the FCR-N market on its own, the storage was unable to respond to the FCR-N demand for over one-third of the time, of which over 90% of the times the storage was empty. Therefore, it is expected that the profitability increases if the storage is every once in a while charged with excess wind power.

If a specific portion of the battery's power is sold to the FCR-N market, that portion cannot be used to charge the battery with wind power during the hours that the capacity is sold in, but the rest of the power can be used to charge the battery (Ruokolainen, 2019, *Fingrid,* 2019e). A solver is run to estimate the optimal percentage of power to be used on the FCR-N market and the optimal state of charge up to which the battery is allowed to be charged by wind power to maximize profitability.

Again, for simplicity, the battery was set to be on the FCR-N market 24/7, which in reality is different. In the real world, offers are submitted for selected hours on the previous evening, based on forecasts and estimates on the reserve's availability. The storage would likely have fewer hours when it's unable to respond to the FCR-N demand, and therefore it would likely be more profitable in reality than in the calculations.

6 Results

6.1 The Effects of the New Market Environment

6.1.1 The Effects of 15-Minute Imbalance Settlement Period

This section covers the results on the calculations of the effects of the 15-minute imbalance settlement period. The first study investigated the relative standard deviation of the 15-minute, 30-minute and one-hour market products in Finland and Germany. The second study examined an average day on the German 15-minute intraday continuous market. Since the studies were based on the analyzation of the German electricity market, it does not necessarily mean that the estimated outcomes will happen on the same scale in Finland.

Part 1: Comparison of Relative Standard Deviations

First, the relative standard deviation (RSD) of the Finnish and German day-ahead volumes in 2016, 2017 and 2018 was calculated. The RSD, also called the coefficient of variation, is the ratio of standard deviation and the mean. The resulting number indicates, how much the data values tend to vary from the mean.

Figure 14 presents the results of the relative standard deviation calculation of the hourly day-ahead prices and volumes in Finland and Germany. The RSD for the volumes was approximately the same for both countries, around 19%. The RSD for the prices was around 29-41% in Finland, 34% on average, and around 40-51% in Germany, 45% on average. This indicates that the volatility of day-ahead prices in Finland is approximately 76% of the corresponding number in Germany.

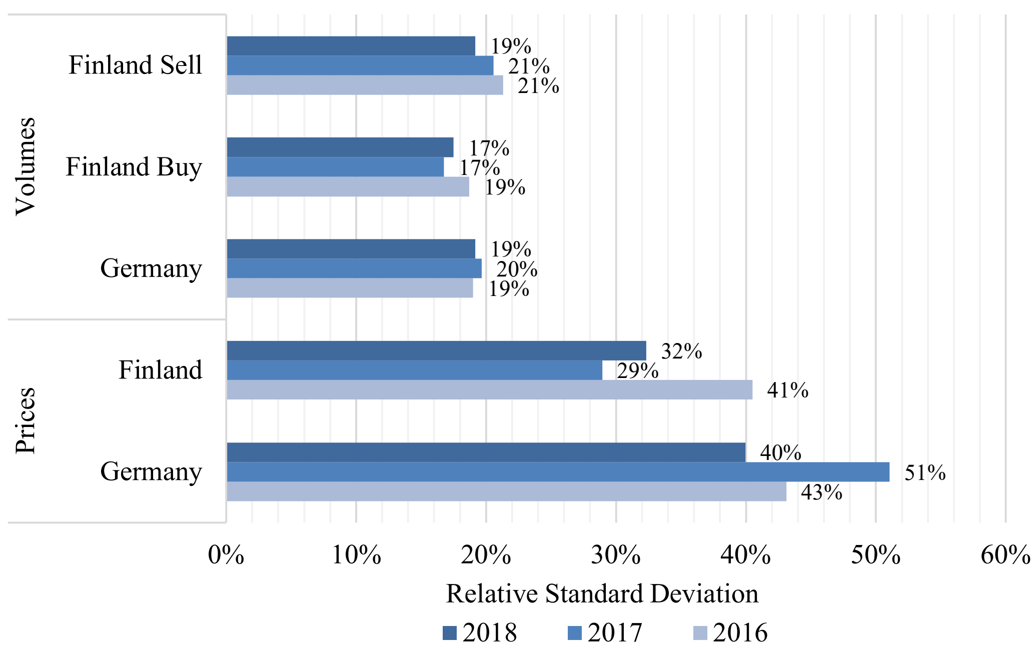

Figure 14 The relative standard deviation of the hourly day-ahead prices and volumes in Finland and Germany in 2016, 2017 and 2018

Next, the RSD of the Finnish and German intraday continuous volumes and prices in 2016, 2017 and 2018 was calculated. All Finnish data has the market time period of one hour, and the German data is divided into 15-minute, 30-minute and one-hour market time periods, and trading exists in each one of them. The 30-minute data was only available starting from 28 March 2017, and due to limited accessibility of resources, in Finland, only intraday data of 2018 was available.

The relative standard deviation of the intraday continuous markets in Finland and Germany are presented in Figure 15. First of all, the RSDs seem to be as great or greater than the RSDs of the day-ahead market. The RSDs of the German intraday volumes from the 15-minute and one-hour market have decreased slightly and the 30-minute market increased significantly over time. The great volatility of the 30-minute volumes may be explained by the fact that the 30-minute intraday continuous market is relatively rarely used.

Figure 15 The relative standard deviation of the intraday continuous prices and volumes in Finland and Germany in 2016, 2017 and 2018

The volatility of the German 15-minute intraday continuous volumes is around 51-63% of the average, which is slightly greater than the volatility of the 60-minute intraday volumes, 37-42% of the average. The prices seem to have no clear shape, except for the 15-minute market lowest prices, which seem to be the greatest of all, and additionally, increasing significantly over time.

The volatility of the hourly intraday continuous weighted average price is 80%, the hourly highest price 82%, and the hourly lowest price 39% in Finland of what they are in Germany on average. The volatility of the hourly intraday continuous volumes is in Finland 167% of what it is in Germany.

There is uncertainty with the data because Finnish intraday continuous data was available for only one year. In Germany, the volatility has varied for the intraday continuous volumes by around 10% and prices by around 30% within the years 2016, 2017 and 2018. The volatility of the hourly day-ahead prices and volumes has varied in Finland around 10% for the volumes and around 40% for the prices within the same years. Therefore, the volatility of the hourly intraday continuous weighted average price is 56-104%, the hourly highest price 58-107%, and the hourly lowest price 27-51% in Finland of what they are in Germany on average. The volatility of the hourly intraday continuous volumes is 150-183% in Finland of what it is in Germany. The hourly products of the German and Finnish intraday continuous market are so different likely due to different market environments. Also, the existence of the German 15-minute and 30-minute markets may affect the volatility of the German 60-minute intraday continuous market.

In addition to comparing the hourly values between Finland and Germany, the hourly and 15-minute values within Germany are compared, to find out the volatility caused by the 15-minute market time period. The volatility of the 15-minute products compared to the 60-minute products was significantly higher. The volatility was for volumes 46%, average prices 15%, highest prices 12% and lowest prices 125% higher in the 15-minute intraday continuous market than in the 60-minute intraday continuous market in Germany.

The relative standard deviation was calculated also for the 15-minute German intraday auction data. The results are presented in Figure 16. The results indicate that the RSD of both prices and volumes is high and has increased over the years.

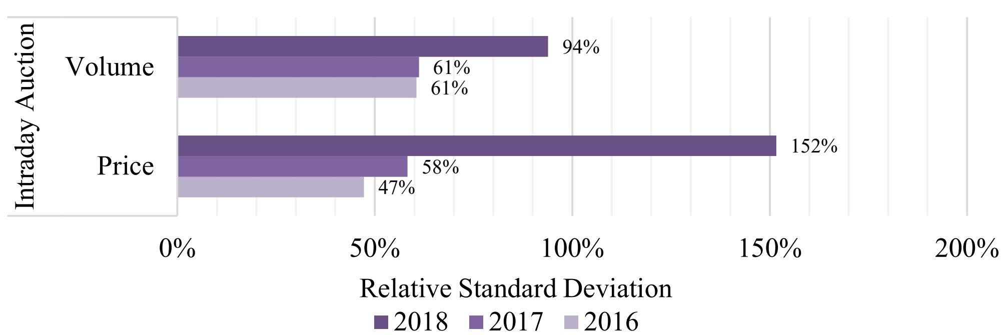

Figure 16 The relative standard deviation of the quarterly intraday auction prices and volumes in Germany in 2016, 2017 and 2018

Also, the balancing markets in Finland and Germany were analysed and the relative standard deviation of the prices and volumes was calculated. The Finnish data has a 60-minute resolution and the German data has a 15-minute resolution. The results are presented in

Figure 17. There is no clear figure, except that all RSDs are high, the volumes seem to have an even higher RSD than the prices, and the German 15-minute market seems to have higher volatility than the Finnish one-hour market.

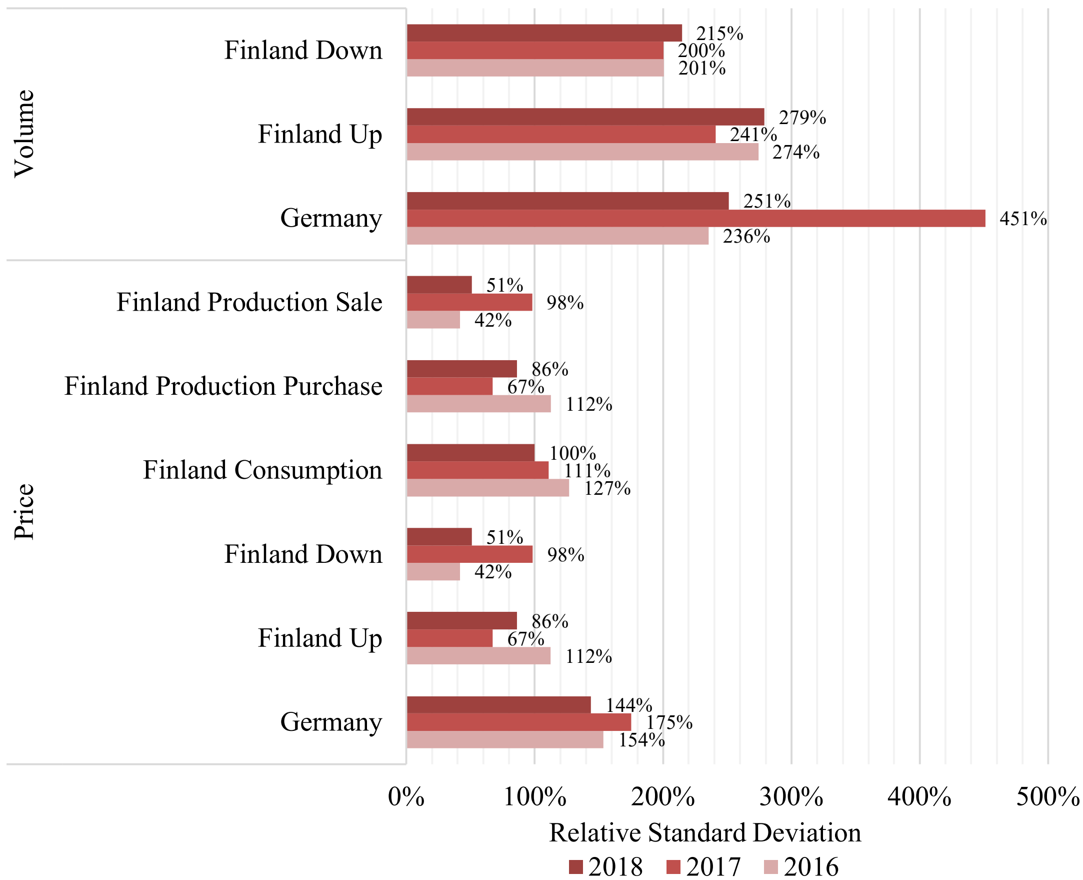

Figure 17 The relative standard deviation of the balancing market prices and volumes in Finland (60-minute resolution) and Germany (15-minute resolution) in 2016, 2017 and 2018

The RSD of the German balancing market volumes is between 236-451%, which is 313% on average, and the RSD of the Finnish balancing market volumes is between 200-279%, which is 235% on average. Therefore, the volatility of the Finnish one-hour balancing volumes is around 75% of the volatility of the 15-minute German balancing volumes.

It should be noted that the volatility of the volumes of hourly products in the day-ahead auction is the same in Finland and Germany and the volatility of the volumes of hourly products in intraday continuous in Germany is 60% of what it is in Finland. Therefore, it could be expected that the implementation of a 15-minute imbalance settlement period would increase the volatility of balancing market volumes by 33-220%.

The RSD of the German balancing market prices is between 144-175%, which is 158% on average, and the RSD of the Finnish balancing market prices is between 42-127%, which is 83% on average. Therefore, the volatility of the Finnish one-hour balancing prices is only around 53% of the volatility of the 15-minute German balancing prices.

The volatility of the average prices of hourly products in intraday continuous in Finland is 80% of what it is in Germany. The volatility of hourly prices in the day-ahead auction market is in Finland 76% of what it is in Germany. This would indicate that if the volatility of the Finnish one-hour balancing prices is 53% of the volatility of the 15-minute German balancing prices, a 15-minute imbalance settlement period in Finland would increase the volatility of prices by 43-50% compared to the hourly imbalance settlement period.

There is however some uncertainty with the data because there is Finnish intraday continuous data for only one year. Again, in Germany, the volatility for the intraday continuous prices and volumes has varied by around 10% for the volumes and by around 30% for the prices, and in Finland, the volatility of the hourly day-ahead prices and volumes has varied around 10% for the volumes and around 40% for the prices within the years 2016, 2017 and 2018. Therefore, taking into account the uncertainties, the implementation of a 15-minute imbalance settlement period would increase the volatility of balancing market prices by 5-95% and the volumes by 33-244%.

Part 2: Where Does the Volatility Come From?

First, to understand better where the volatility in the German 15-minute intraday and balancing market comes from, a visual figure from a random day is created (Figure 18). Wednesday 8 August 2018 was selected because there were trades within the 30-minute market throughout the whole day, which is rare. The 60-minute day-ahead, 15-, 30- and 60-minute intraday continuous and 15-minute intraday auction market prices in Germany are visualized.

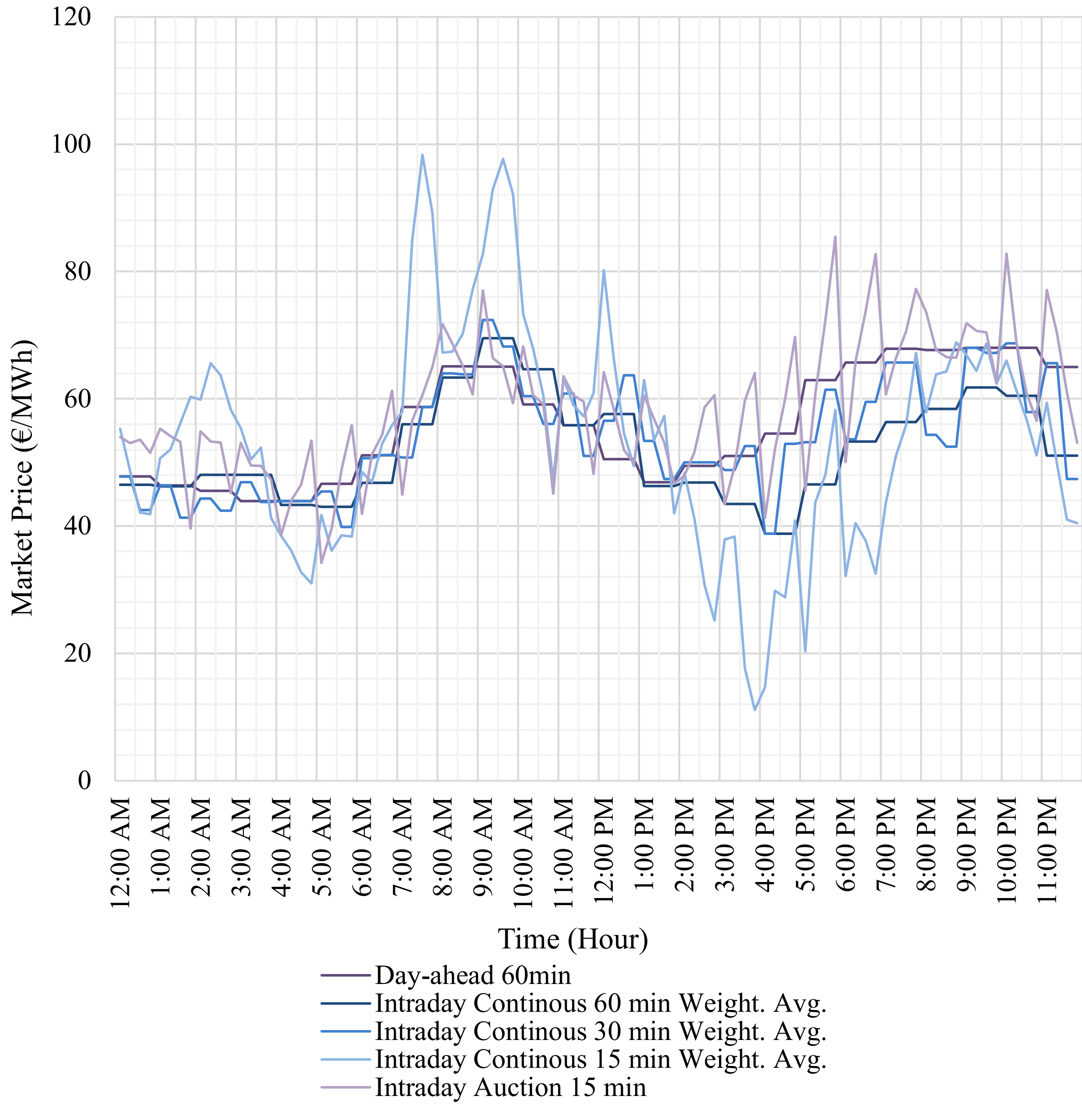

Figure 18 The behaviour of different electricity market prices on Wednesday 8 August 2018

Looking at the intraday auction and continuous and day-ahead auction markets on 8 August 2018 in Germany in Figure 18, it is clear that the 15-minute intraday auction and especially the 15-minute intraday continuous market price has a very volatile figure compared to all other market prices. The day-ahead, the 30- and 60-minute intraday continuous market prices seem to be somewhat aligned.

Next, an average 2018 day in Germany for the day-ahead auction and intraday continuous markets, both prices and volumes, is visualized in Figure 19. All quarterly averages are divided by their yearly average to present all data on the same scale. The first quarters each hour in the 15-minute intraday continuous prices and volumes are indicated with a darker circle. There is a clear shape in the intraday continuous price – while the day-ahead price decreases, the first quarter has the highest price and the last quarter has the lowest price. When the day-ahead price increases, the first quarter hast the lowest price and the last quarter has the highest.

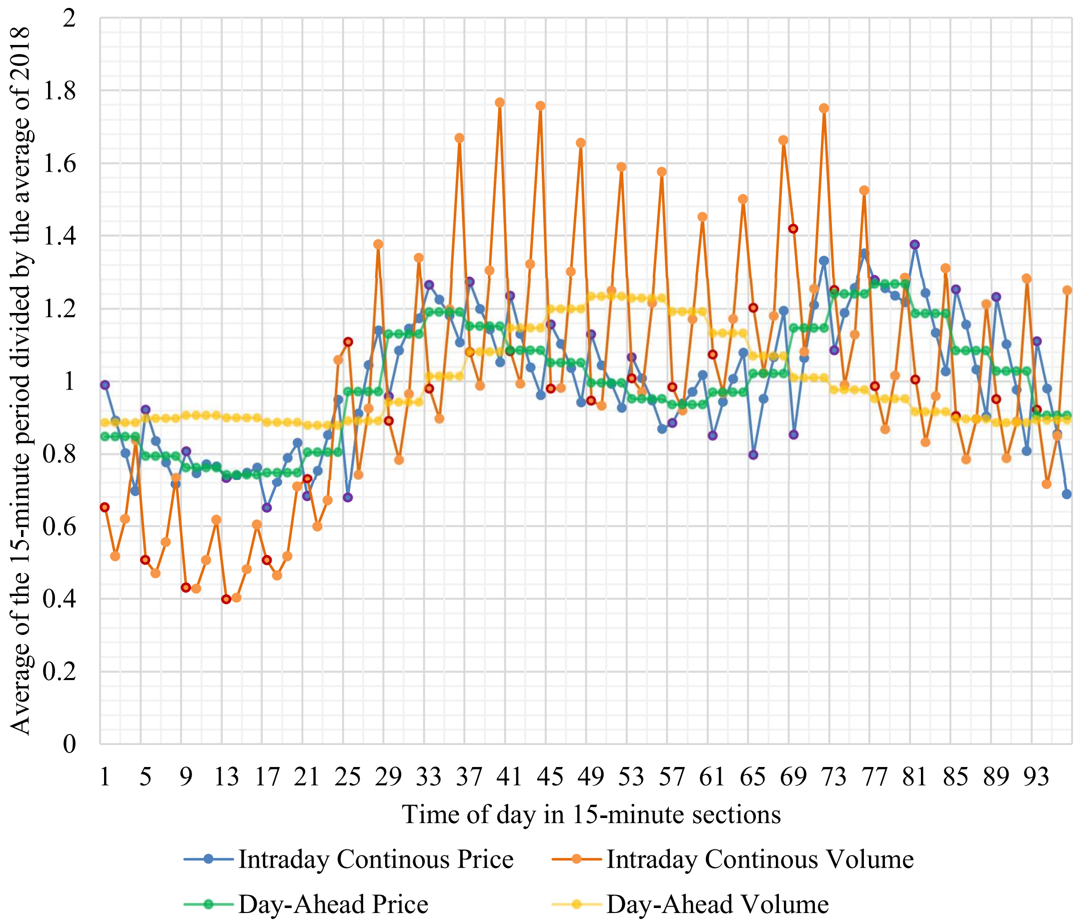

Figure 19 An average 2018 day on intraday continuous and day-ahead markets in 15-minute sections in Germany

The reason behind the price shape is likely the 15-minute imbalance settlement period. Some similar analyzation methods have been made for the German intraday continuous markets blaming weather forecasts (Kiesel and Paraschiv, 2017) and German intraday auction markets blaming a special behaviour on the market (Solovian, 2019).

The shape of intraday continuous prices in Figure 20 is similar to the shape of intraday auction prices, which Solovian (2019) has presented. First of all, the intraday continuous prices seem to revolve around the day-ahead price. Figure 20 presents one section of Figure 19, the section of 9:00-12:00 AM in 2018 in Germany, taking a closer look at the intraday continuous and day-ahead prices when the day-ahead price is descending. Figure 20 presents the average value of a 15-minute period of the day in 2018 which has been divided by the yearly total average of 2018 to have the day-ahead and intraday prices on the same scale.

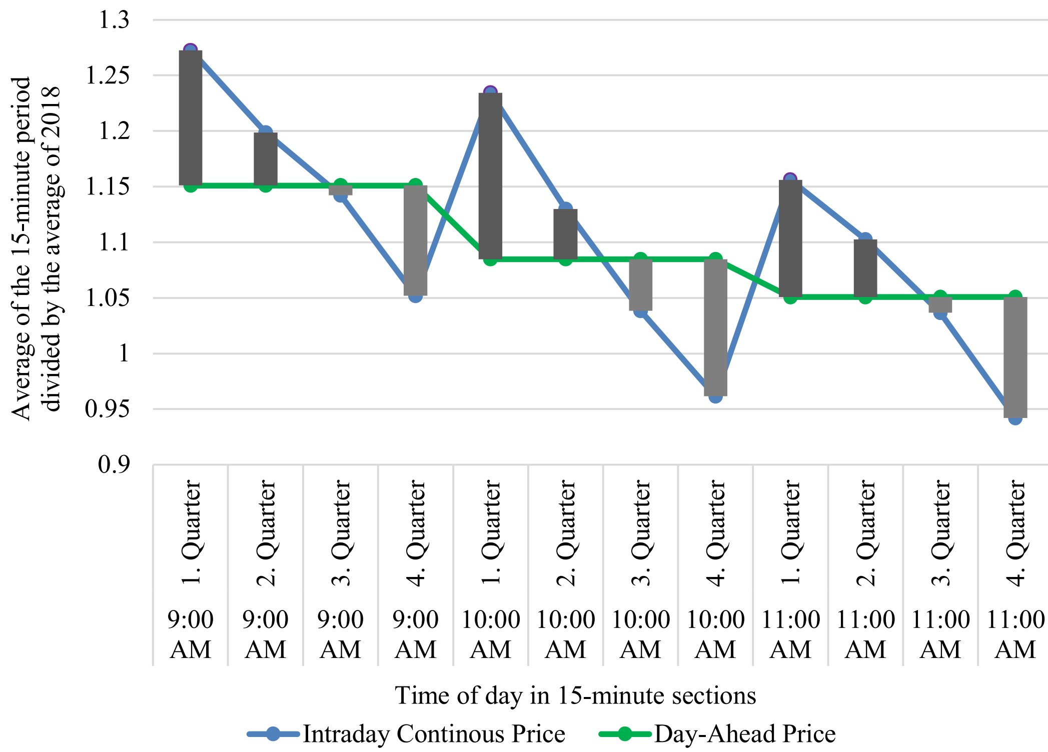

Figure 20 The intraday continuous and day-ahead average prices of each quarter between 9:00-12:00 AM in 2018 divided by the total averages in 2018 in Germany

This shape exists because the BRPs have promised a specific production for each quarter. While they need to stay within the hourly production in the day-ahead market, they also need to have a descending amount of production to match the descending demand. In the first quarter, many market players want to buy electricity from the intraday market to maintain their balance during the first quarter, and the price level is high. During the last quarter, there is less demand for electricity and many market players want to sell their electricity in the intraday markets, and the prices drop. This shows evidence that the 15-minute imbalance settlement period pushes market players to avoid balancing fees by purchasing and selling power in the intraday markets.

The analyzation also indicates that the intraday prices can be somewhat predicted from the day-ahead prices. When the day-ahead prices are decreasing, there will be most demand for the first quarter and most excess power on the last. When the day-ahead prices are increasing, there will be most excess power for the first quarter and most demand for the last. A smart market player checks out the upcoming day-ahead prices and buys intraday continuous power before it becomes too expensive and sells it before it's too cheap.

Let's have a look at Figure 19 again, now focusing on volumes instead of prices. The volatility of the intraday continuous volumes seems to increase during the hours of the largest volumes. The hourly shape resembles a tick-mark (✓) with a smaller first quarter than the last quarter. The shape seems to be closer to the intraday and day-ahead prices than the day-ahead volumes since during the first hours of the day the volumes seem to be especially low, and there is a dip in volumes in the early afternoon.

There is no tick-mark shape in intraday auction volumes, only in intraday continuous volumes (Kiesel and Paraschiv, 2017, Solovian, 2019). The reason behind the tick-mark-shape is likely related to the difference between these two markets: in the auction market, there is a same price for everyone during the hour, while in the continuous market, there are different prices for different deals. Or, maybe electricity is traded more in the intraday auction market than in the intraday continuous market for the first quarter because the prices in the intraday continuous market are high.

6.1.2 Variable Renewable Energy Sources

This section presents the results of the study of the effect of intermittent renewables on electricity markets from the viewpoint of an independent wind power producer. First, the relationship between wind power production in Finland and several independent wind turbines is presented. Second, the correlation between wind power production and wind power forecast error with intraday and balancing markets is analysed. Third, the relationship between the regulating hour and the forecast error is examined. Next, the correlation between the wind power forecast and the day-ahead price is evaluated. Last, the average day concerning the wind power forecast error is visualized.

First, the coefficient of determination of Finnish national wind power production with nine single wind turbines in summer 2019 and three single wind turbines in winter 2018-2019 was calculated. The wind power plants are from two wind farms, located 200 km from each other. The results are presented in Figures 21 and 22. The results from summer 2019 in Figure 21 show that the correlation between the overall wind production in Finland and single wind turbines varies and was 31% on average, which was lower than the correlation with entire wind farms, 37% on average, which as such was lower than the correlation with a group of wind farms, 45%. The same phenomenon occurred in winter 2018-2019 (Figure 22). This indicates that the wind production in Finland could be heterogeneous, because the production from single wind farms correlates only little with the national wind power generation, and the correlation increases significantly when wind power plants in several locations are included. The more spread the wind farms are, the higher their production correlates with the national wind power production.

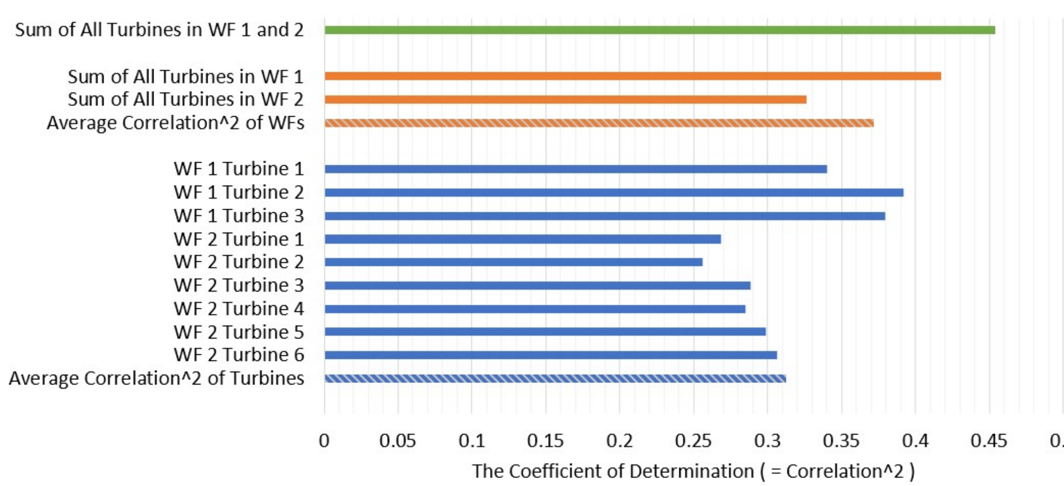

Figure 21 The coefficient of determination (R^2) of the 3-minute momentary wind power production data of Finnish wind turbines in two wind farms with the 3-minute momentary wind power production data in Finland between 4 July and 15 August 2019

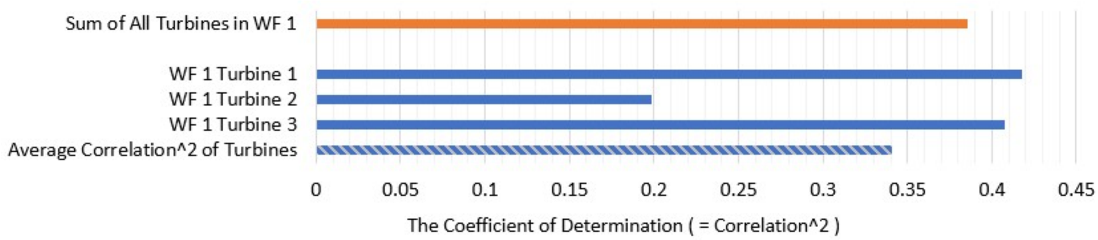

Figure 22 The coefficient of determination (R^2) of the 3-minute momentary wind power production data of Finnish wind turbines in two wind farms with the 3-minute momentary wind power production data in Finland between 26 November 2018 and 16 January

Next, the relationship between up- and downregulating hours and wind power production volumes was analysed. The average wind power production volume was around 18% bigger during the down-regulating hour compared to the up-regulating hour in 2016 and 2017. In 2018 the corresponding number was 11%. This indicates that when there is more wind, there is more down-regulation and vice versa. However, the number is so small that the effect seems to be very slight.

Additionally, the correlation between Finnish total wind power production and imbalance prices in 2016, 2017 and 2018 was analysed. The correlation, presented in Table 6, was very low, but negative. Most correlation occurred in 2018, when wind power production explained 2,94% of the downregulating price and the imbalance production sale price, affecting them negatively. This is a very low number, and therefore the correlation is rather insignificant and can be ignored.

		Price up	Price down	Imbalance price consumption	Imbalance price production purchase	Imbalance price production sale	Volume up	Volume down
2016	R^2	0.0032	0.0067	0.0027	0.0032	0.0068	0.0064	0.0065
	Correlation	-0.0566	-0.0818	-0.0523	-0.0563	-0.0825	-0.0801	-0.0806
2017	R^2	0.0244	0.0045	0.0091	0.0242	0.0048	0.0026	0.0087
	Correlation	-0.1561	-0.0673	-0.0953	-0.1555	-0.0692	-0.0506	-0.0930
2018	R^2	0.0130	0.0294	0.0124	0.0131	0.0294	0.0007	0.0001
	Correlation	-0.1140	-0.1714	-0.1113	-0.1144	-0.1716	-0.0263	0.0076

Table 6 The correlation between Finnish total wind power production and balancing power markets in Finland in 2016, 2017 and 2018

Also, the correlation between Finnish total wind power production and intraday prices and volumes in 2018 was calculated. The correlation, presented in Table 7, was again rather low, but higher than the correlation with balancing market prices. The effect was again negative, so when there was more wind power production, the intraday prices were slightly smaller on average. The highest correlation was with the lowest price of the hour, 4.47%, and with the average price of the hour, 4.38%. There was no correlation at all with wind power production and intraday volumes.

		High	Low	Last	Avg	Volume
2018	R^2	0.0273	0.0447	0.0331	0.0438	0.0000
	Correlation	-0.1651	-0.2114	-0.1819	-0.2094	0.0055

Table 7 The correlation between Finnish total wind power production and intraday markets in Finland in 2018

The Finnish total wind power forecast error was calculated, by subtracting each hourly forecast from the actual hourly production. The correlation between the forecast error and balancing prices and volumes in 2017 and 2018 was calculated and presented in Table 8. All correlations were negative, and there was no significant correlation. There was most correlation, 2.97%, with the downregulating volumes in 2017. There was again some correlation, 2.49%, with the downregulating price and imbalance production sale price. However, these numbers are low, so the relationship with the wind power forecast and the balancing power markets is insignificant.

		Price up	Price down	Imbalance price consumption	Imbalance price production purchase	Imbalance price production sale	Volume up	Volume down
2017	R^2	0.0083	0.0038	0.0088	0.0083	0.0040	0.0172	0.0297
	Correlation	-0.0911	-0.0617	-0.0941	-0.0909	-0.0629	-0.1312	-0.1722
2018	R^2	0.0075	0.0249	0.0114	0.0075	0.0249	0.0077	0.0014
	Correlation	-0.0866	-0.1577	-0.1068	-0.0869	-0.1579	-0.0878	-0.0379

Table 8 The correlation between Finnish total wind power forecast error and balancing power markets in Finland in 2017 and 2018

The Finnish total wind power forecast error was compared with the intraday markets in 2018. The correlation is presented in Table 9. There was most correlation with the lowest and average price of the hour, 2.89% and 3.20%. There was no correlation with the volumes. All correlations were negative and relatively small. Therefore, there seems to be no significant effect on forecast error to intraday prices.

		High	Low	Last	Avg	Volume
2018	R^2	0.0184	0.0289	0.0256	0.0320	0.0015
	Correlation	-0.1356	-0.1699	-0.1599	-0.1789	-0.0390

Table 9 The correlation between Finnish total wind power forecast error and intraday markets in Finland in 2018

Forecast errors were divided into sections of 50 MWh/h, and the amount of up-, down- and nonregulating hours within each range is calculated (Figure 23). If the forecast error is positive, there has been more production than was expected, and if the error is negative, there has been less. Most errors occurred between -50 and -100 MWh/h. There are significantly more down- than upregulating hours when the forecast error is positive or between 0 and -100. For some reason, the turning point is somewhere around -100. The reason for the negative turning point may be that wind power BRPs protect themselves from large imbalance costs by announcing a smaller forecast than they actually forecasted.

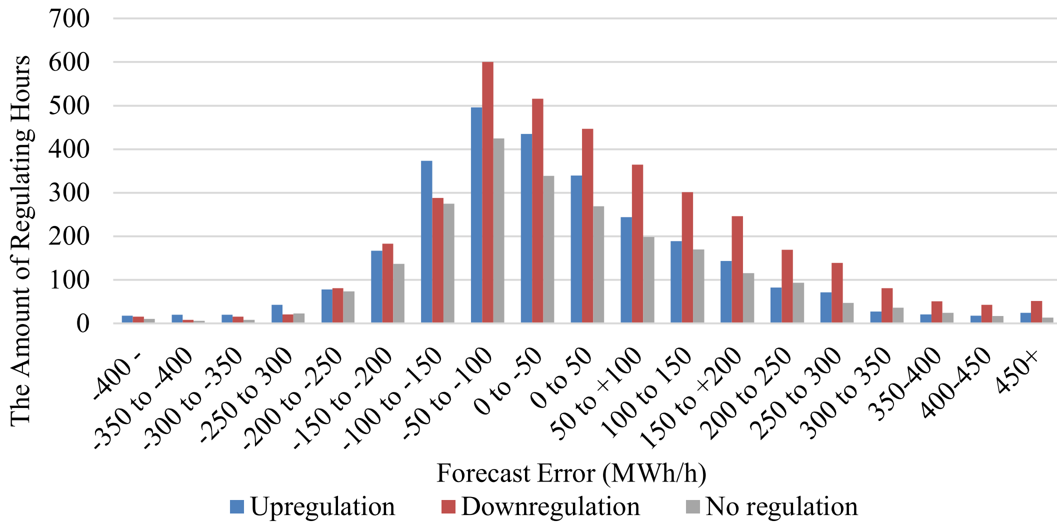

Figure 23 The amount of up-, down- and nonregulating hours within each forecast error range in Finland in 2018

Next, the correlation between the hourly wind power previous day forecast and the day-ahead price in Finland was calculated. The correlation in 2017 was -0.21708 and in 2018 was -0.21300, and the corresponding R-squared values were 0.04713 and 0.04537. This means that in 2017 and 2018 the wind power forecast explained 4.7 % and 4.5% of the day-ahead price variance, reducing the price slightly. There was no data available from the previous years, and therefore only two years were able to include in the calculations.

The average day for wind power forecast error in 2017 and 2018 was calculated, with 24 averages, one for each hour. The results are presented in Figures 24 and 25. There is a clear shape in both 2017 and 2018, which indicates that during the day, the forecast error is usually negative, and during the night, it is usually positive. This means that the wind power forecasts are usually too high for the day and too low for the night. The figure steepens from 2017 to 2018, when wind power production increased from an average of 470 MWh/h to 615 MWh/h.

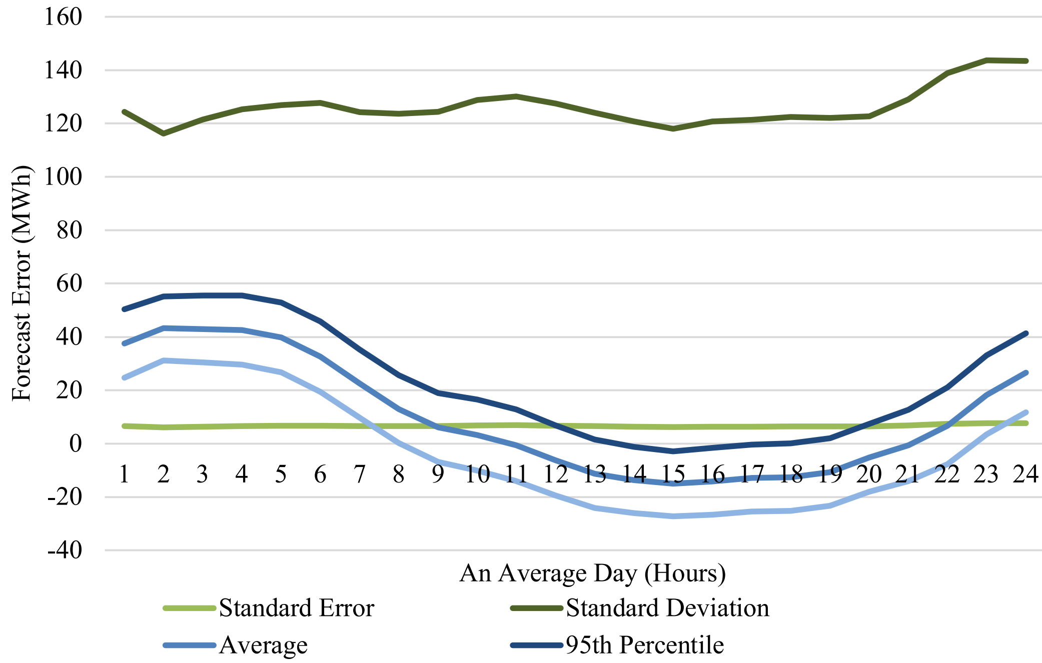

Figure 24 Wind power forecast error's average, standard deviation and standard error for each hour of the day in Finland in 2017

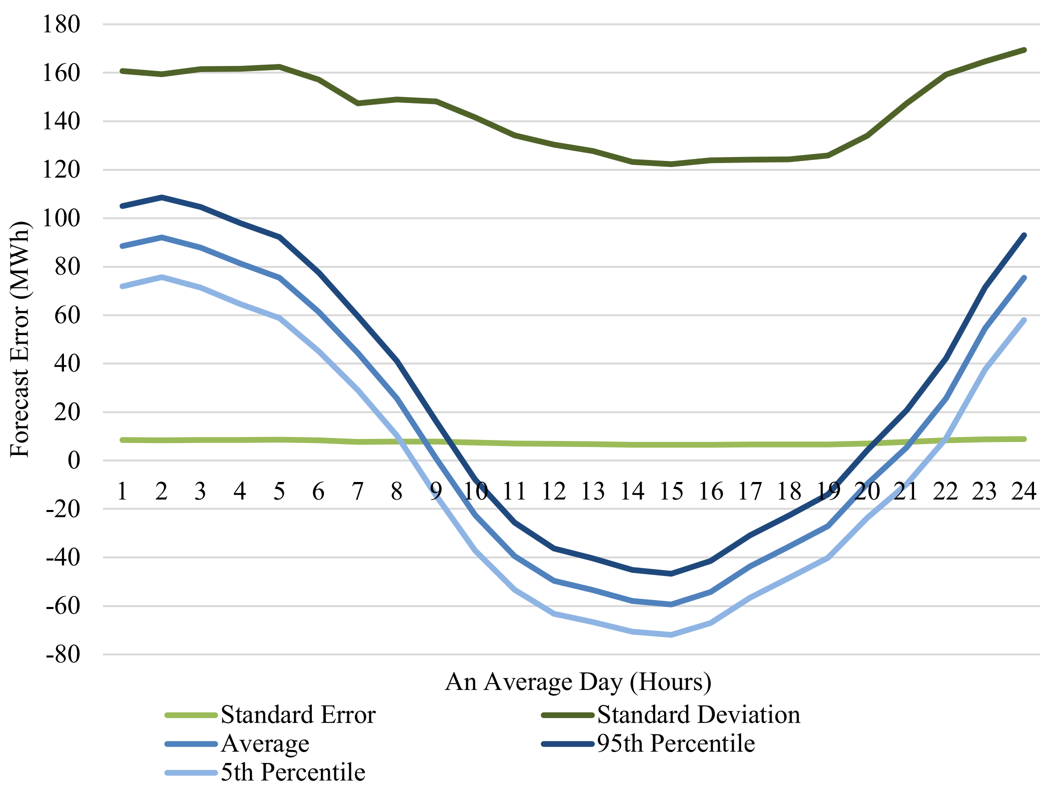

Figure 25 Wind power forecast error's average, standard deviation and standard error for each hour of the day in Finland in 2018

An average day for wind power production in 2017 and 2018 is presented in Figure 26. It has somewhat the same shape as the wind power forecast error. During the windiest hours, there is likely more production than forecasted, and during the least windy hours, there is likely less production than forecasted.

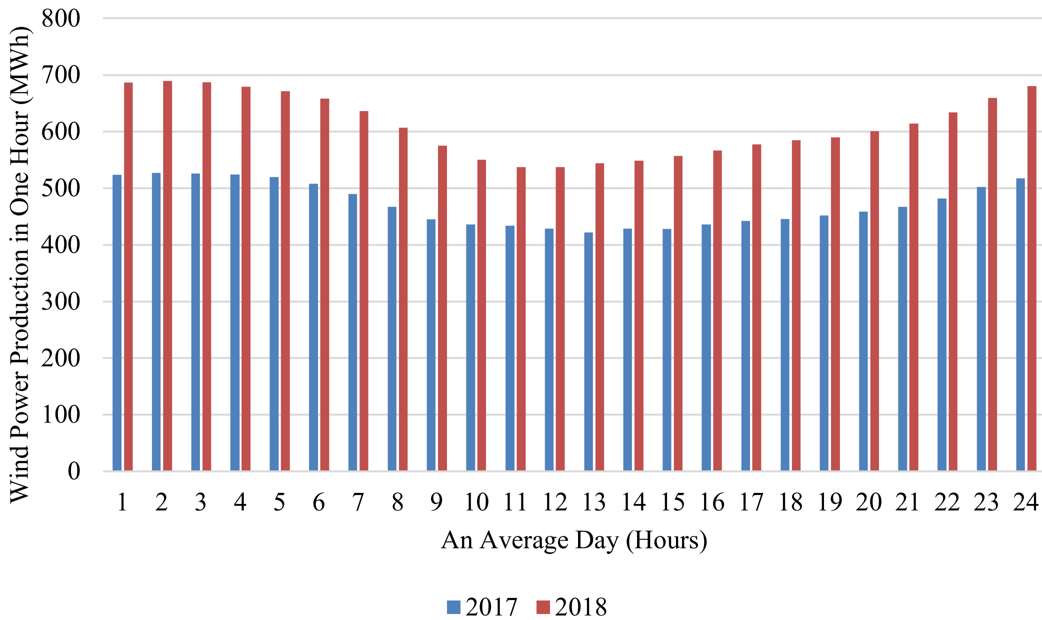

Figure 26 The average wind power production for each hour of the day in 2017 and 2018 in Finland

6.2 Profitability of Different Market Scenarios

6.2.1 Onshore Wind Power

This section presents the results of the analysis of wind power profitability in different markets. First, the LCOE of wind power is selected and the average PPA scale is researched. Next, the correlation between the day-ahead market and wind power production is calculated. Then, the revenues and expenses of being on the spot market or using a PPA are compared.

Wind Power Costs

According to the International Renewable Energy Agency (*IRENA*, 2019), the global onshore wind power investment costs have reduced to around 1.5 million USD per MW in 2018. IRENA also mentions that the capacity factor, the average power generated divided by the rated peak power, has increased up to 34 % in 2018.

The levelized cost of electricity (LCOE) of global onshore wind power with a lifetime of 25 years in 2010-2018 according to IRENA (2019) has been decreasing. IRENA (2019) states it was around 56 USD / MWh in 2018, which equals around 47.50 € / MWh based on the average exchange rate of 2018 (*Statista,* 2019). This number is a global average. There are some factors that are significantly different in today's Finland. This study calculates the LCOE again with more accurate values.

First of all, IRENA's calculations have an economic lifetime of 25 years per turbine. In reality, the lifetime of wind turbines can be much longer. Both Vestas (2018) and Siemens Gamesa (2018) provide a lifetime extension service. Vestas does not publicly mention the exact lifetime extension, but Siemens Gamesa mentions it to be a guarantee up to a 30 years lifetime. Also, according to Rubert et al. (2019), the wind turbine lifetime may reach up to 35 years.

The wind power LCOE depends mainly on the investment costs, the capacity factor, the interest rate r, the operation and maintenance costs and the lifetime of the wind farm. The interest rate r is the weighted average cost of capital (WACC). According to IRENA (2019), the interest rate in the OECD countries is around 7.5%. and due to current particularly low interest rates, this may be even lower.

IRENA's LCOE is based on OECD countries' 2011 and 2015 operations and maintenance (O&M) costs 20-30€/MWh (*IRENA*, 2019). In Finland, in 2019, the number is likely significantly lower. According to Vakkilainen and Kivistö (2017), the operation and maintenance cost varied in 2017 between 10-15 €/MWh in Finland, and in large-scale wind farms, it was even lower. Therefore, this study used a number of 9 €/MWh.

The investment costs per MW decrease while the wind farm size increases. The global 1.5 million USD/MW IRENA mentions (2019) may be correct for a global average wind farm in 2018, but since the scale of wind farms is increasing, the cost is likely decreasing. 1.5 million USD was around 1 270 000 € in 2018 (*Statista,* 2019). Therefore, this study uses the investment cost of 1.25 M€/MW. For large scale wind farms, this cost is likely even smaller.

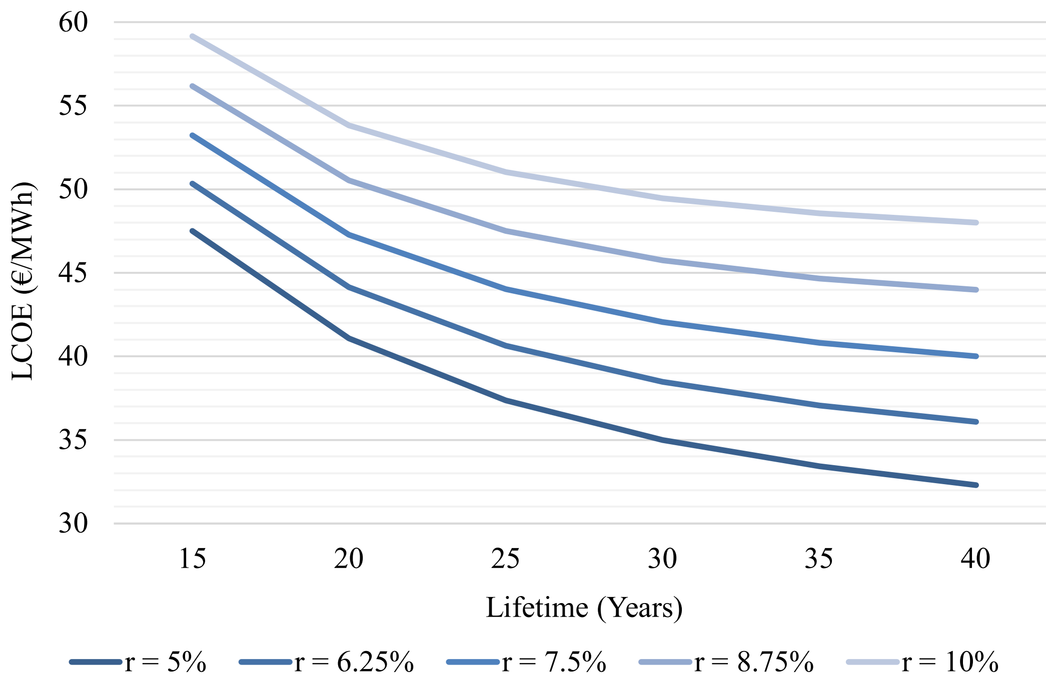

Figure 27 The LCOE of a wind farm with a 9 €/MWh O&M cost, 1.25 M€/MW investment cost and a 34% capacity factor with different interest rates r

The results of the study are presented in Figure 27. If the lifetime of a wind farm is 30 years and the WACC is 6.25%, the LCOE is 38.47 €/MWh. This number is for an average-sized wind farm, and therefore it will likely be even smaller for larger wind farms. For large-scale wind farms, if the investment costs are only 1.1 million euros per MWh and the maintenance costs only 8 €/MWh, the corresponding number is 33.93 €/MWh. Therefore, in today's Finland, the LCOE scale 34-38 €/MWh is much more accurate than IRENA's (2019) 47.50 €/MWh.

Power Purchase Agreement

The benefit of PPAs is the security of a stable price for a specific time frame. However, there are several challenges related to PPAs. First of all, there are not many buyers in the market. It is very challenging for a power producer to find someone to make a deal. Second, the price level of PPA's is relatively low. It may not be enough for the power producer. (*Finnish Wind Power Association,* 2019)

The price level of PPAs is hard to estimate since the deals are confidential, but according to Jonas Metzger of investment fund KGAL, the price level of 10-year Nordic PPAs is around 29-31 €/MWh. This means the price level of PPAs is challengingly low for wind power producers, whose LCOE varies somewhere around 34-38 €/MWh. (Tigerstedt, 2019)

Day-Ahead Market

Hourly average wind power values in Finland (MW) and in three independent wind turbines (kW) were calculated from 3-minute averages between 26 November 2018 – 16 January 2019. These hourly values were compared with the day-ahead price and buy and sell volumes by calculating their correlation. The results in Table 10 show that there is a significant correlation between the buy volumes and the wind power production in Finland. All correlations were negative. For example, the wind power production in Finland explained 23.43% of the variance of the day-ahead buy volumes, reducing the volumes.

		Wind Power Finland	Wind Power Turbine 1	Wind Power Turbine 2	Wind Power Turbine 3
Buy Volumes	R^2	0.2343	0.1329	0.1181	0.1209
	Correlation	-0.4841	-0.3646	-0.3436	-0.3477
Sell Volumes	R^2	0.0675	0.0964	0.1035	0.0973
	Correlation	-0.2598	-0.3105	-0.3217	-0.3120
Day-Ahead Price	R^2	0.1115	0.0780	0.0267	0.0709
	Correlation	-0.3339	-0.2793	-0.1633	-0.2663

Table 10 The correlation of the day-ahead prices and volumes with national and single wind turbine hourly average production power between 26 November 2018 and 16 January 2019 in Finland

If all wind power forecasted in Finland was in the spot market and the forecast errors were sold or compensated in the balancing power market, the spot market revenue would be on average 44.67 € / MWh produced and the balancing power costs on average 0.8578 € / MWh produced in 2018. The corresponding numbers for 2017 would be 31.66 € / MWh and 0.5012 € / MWh. The day-ahead price average of 2018 was around 46.80 € / MWh and in 2017 it was around 33.19 € / MWh.

This means the profit of wind power in the spot market was only slightly smaller than the average spot price. This also indicates that the balancing of wind power in Finland is relatively cheap. It was only 1.58% of the day-ahead profit in 2017 and 1.92% in 2018. One reason behind this may be that wind power producers likely report a lower forecast than they truly forecast, to be on the safe side.

Since the average day-ahead profit for a wind power producer in 2018 was 44.67 €/MWh, after reducing balancing costs, the profit was around 43.82 €/MWh. If the LCOE of wind power is around 34-38 €/MWh, the profit for a wind power producer was roughly 5.8-10.8 €/MWh. This means 1 MW of installed wind power with a 34% capacity factor could create a yearly profit of roughly 17 300 – 29 200 € with 2018 spot and balancing prices.

The price can be protected by selling futures. If the true day-ahead price is higher, the power producer loses. If it is lower, it wins. Wind power producers are willing to lose slightly from their profit to reduce their risks (Gersema and Wozabal, 2017).

The Future for a Wind Power Producer

After the implementation of the 15-minute imbalance settlement period and the single-price model, the balancing costs will likely rise. As found in chapter 6.1.1, the 15-minute ISP will push inflexible BRPs to avoid imbalances by increasing their trading on the intraday market. The volatility of intraday market prices will increase and therefore it will be less profitable to produce intermittent electricity such as wind power.

The price volatility of intraday markets can be decreased by reducing forecast errors of wind power (Gürtler, Paulsen, 2018). Also, the future profitability will likely increase when being active on the market and optimizing the behaviour based on day-ahead and intraday prices (Cai et al., 2016).

6.2.2 Electricity Storages

This section presents the results of the analysis of BESS's profitability in different markets. First, the potential of the selected FCR-N and balancing markets is estimated. Next, the profitability of an electricity storage on these markets is calculated.

FCR-N Potential

The hourly FCR-N prices of years 2011-2018 were put in order of magnitude in Figures 28 and 29. Years 2017 and 2018 have the least 0€/MWh-prices. Years 2015-2018 have had a very homogenous shape within the 100.-4500. highest values, which cover around 50% of the year. The FCR-N prices seem to become more and more secure from the reserve provider's point of view.

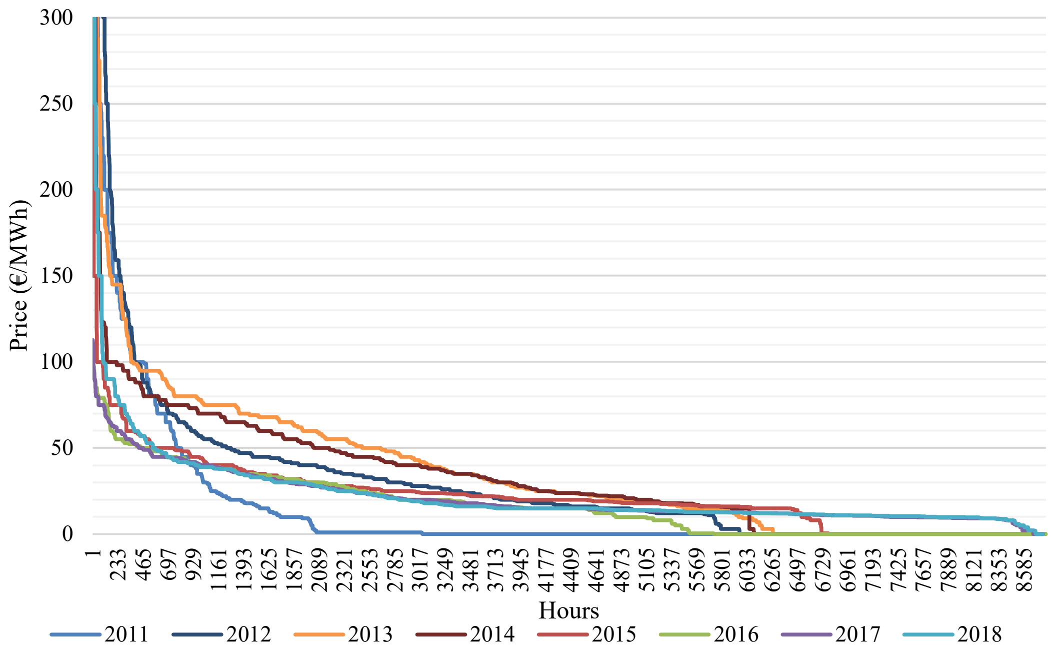

Figure 28 The hourly FCR-N prices of the year in the order of magnitude, not showing values over 300 €/MWh

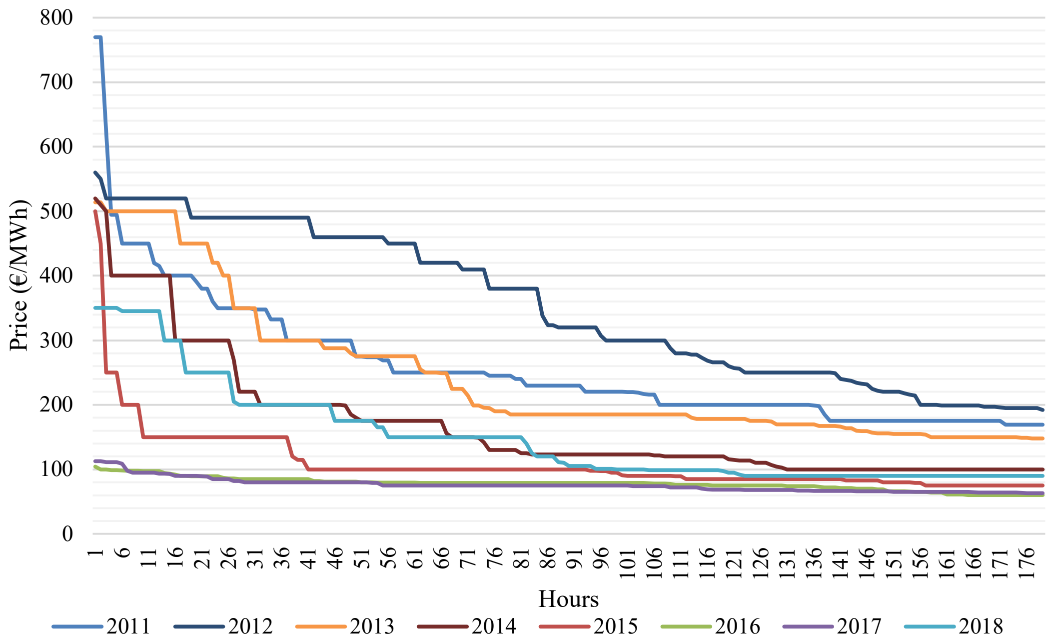

Figure 29 The Hourly FCR-N prices of the year in the order of magnitude, including the highest 180 hours

A Lithium-Ion Battery on the FCR-N Markets

First, the net present value (NPV) of a 3 MWh electricity storage with an interest rate of 6% on the FCR-N markets, based on 2018 and 2017 FCR-N prices and frequencies, was calculated. Next, the breaking point of profitability, the point where the storage costs are low enough to result in a positive NPV, was calculated. The calculations assume that the markets act continuously as they did during the examined period 2018 or 2017. The calculation is based on a 15-year battery calendar life because, according to IRENA (2017), the average battery calendar life of a lithium-ion battery was 12-15 years in 2016. IRENA (2017) defines battery costs per MWh of storage capacity and, to create comparable results, the same is done in this thesis. The cost of storage includes all investment, operations and maintenance costs. The calculations did not take into account that not all offers are accepted. The penalty of not being able to provide or consume energy at times was considered.

An optimizer was run for a 1 M€/MWh 3 MWh electricity storage in 2018 to find the power level that results in the best NPV, having a maximum of 1 MW per MWh. The results indicate that the greater the power, the greater the NPV is. If penalties were considered, the optimal storage power would be 3 MW for a 3 MWh storage, resulting in -1 816 k€ loss for the 1 000 k€/MWh storage. The breaking point of profitability for a 3 MW and 3 MWh storage would be that the storage would need to cost 394 645 €/MWh or less if the penalties were considered.

In 2018, this 3MW to 3MWh scenario would result in 2.03 full cycles per day, which would equal quite the average of an LTO storage, but too high for other lithium-ion storages. However, this scenario would have an even slightly smaller cost than the lowest cost of LTO storages, which is around 428 €/kWh, and therefore this scenario is challenging to achieve in reality (*IRENA*, 2017). Also, the interest rate of 6% may be underestimated, since the rates are hard to predict.

The same calculations were calculated for 2017 instead of 2018. In 2018, the FCR-N prices were higher, which shows as a higher NPV without penalties but a lower NPV with penalties. This means high prices do not necessarily mean high profit, since the high prices may happen to be when there is a demand for only charging or only discharging for a long time in a row, resulting in an inability to take action.

The optimizer was run for the same values 1 M€/MWh and 3MWh in 2017 finding the solution that brings the highest NPV and resulted in 3MW power when the maximum was 1 MW / MWh. This would result in -958 k€ loss for the 1 000k€/MWh storage. The breaking point of profitability for a 3 MW and 3 MWh storage would be 680 820 €/MWh or less if the penalties were considered.

In 2017, this 3 MW to 3 MWh scenario would result in 2.10 full cycles per day, which would also equal quite the average of an LTO storage. The breaking point of storage cost for profitability is significantly higher than in 2017. The numbers are perfectly within the range of IRENA's LTO storage cycle life and costs (2017).

There are some significant differences between the calculations and reality, of which the latter likely has better profitability because of the 3- or 5-minute intervals of the data. There may be a charging period in reality within a 3-minute period that appears as a discharging period in the data. This would result in more full charging-discharging cycles. Additionally, the battery might not empty in reality as soon as in the calculations, if, in reality, it is able to be charged in between the discharge-periods. This would result in less penalty and more profit. The same result is emphasized if the battery can be charged for slightly less than 3 minutes, it is not charged in the calculations, because in the calculations the minimum is the 3-minute interval. Some of these issues are slightly more thoroughly discussed in chapter 5.2.2. section "A Lithium-ion Battery on the FCR-N Markets".

In 2017, 35% of the year the storage was unable to react to the demand. In 2018, the corresponding number was 40%. In 2017, 91.1% of times when the storage was unable to respond to the FCR-N demand was when it was empty. The corresponding number was 92.8% in 2018. This could possibly be solved by combining the storage with electricity production. Chapter 6.2.3 calculates the profitability of the combination of wind power and electricity storages.

A Lithium-Ion Battery on the Balancing Markets

The profitability of a lithium-ion storage on balancing markets was calculated. First, the capacity was set to 2 MWh and power to 1.9 MW, having the minimum state of charge at 5% which is 0.1 MWh. This means the battery charges from minimum to full capacity in one hour. The charging time period was set to one hour due to the price and regulating direction data has a one-hour resolution.

First, the battery was set to be charged and discharged on the first possible moment. The annual profit was negative, even without taking the investment cost into account. Second, the battery was set to "predict the future" perfectly and in case there are several up-regulation hours in the row, it would discharge only during the highest price hour, and if there are several down-regulating hours in a row, it would charge only during lowest price hour. The annual profit became 18949 € in 2017 and 19021 € in 2018. However, in case the battery cost 500000 €/MWh, it would cost 1 M€ and therefore the NPV for 15 years would be around -815 000 €/MWh for both 2017 and 2018. This means the battery would definitely not pay itself back. Even if the battery was the cheapest on the market, somewhat 200k€/MWh, it would have an NPV of around -215 000 € for both 2017 and 2018, which means there is currently no way to make a profit only operating on the balancing power markets with a battery storage.

6.2.3 Wind Power with Electricity Storages

The potential of electricity storages paired with wind power production was investigated in winter 2018-2019 and summer 2019. The calculations were similar to calculations in chapter 6.2.2, except that now excess wind power resulting from erroneous wind power forecasts was used to charge the battery. Again, a lithium-ion storage, having a 15-year calendar life, was selected. The net present value (NPV) of a 3 MWh electricity storage with an interest rate of 6% on the FCR-N markets combined with wind power production was calculated. Also, the breaking point of profitability, the point where the storage costs are low enough to result in a positive NPV, was calculated. The cost of storage includes all investment, operations and maintenance costs. This calculation did not take into account that not all FCR-N offers are accepted. The calculation takes into account that the electricity charged in the battery cannot be sold as balancing energy. The power-to-energy ratio was again 1:1.

A solver was run and it found that 55% is as an optimal state of charge up to which the battery should be allowed to be charged by wind power. The solver also found that the optimal portion of power to be utilized for FCR-N was around 80% in the winter and 85% in the summer. The rest of the power is utilized to charge the battery with excess wind power if there is some in one of Ilmatar wind farms, and only up to the 55% state of charge.

The results show that for a 3MW and 3MWh storage costing 1 M€/MWh the net present value for an electricity storage is -1 218 000 € if the 15-year lifetime of the storage is like winter 2018-2019, and +2 334 000 € if the 15-year lifetime of the storage is like summer 2019. This indicates that a 1 M€/MWh storage would be profitable if excess wind power is used to charge the battery when it's state of charge is less than 55%. This means the combination of wind power generation and a battery energy storage increases the profitability of the storage. The breaking point of profitability for storage costs would be for winter 594 000 €/MWh and for summer 1 778 000 €/MWh. The difference between summer and winter can be explained by the difference in FCR-N prices. During summer, the prices and therefore the profit is higher than during winter.

If the 15-minute ISP and a 1-price imbalance settlement model are implemented, using wind power forecast errors to charge or charge and discharge a battery, the losses in balancing power will likely be smaller and the profit in saving in balancing power costs is higher. Studies have found that a lithium-ion battery storage will improve the profitability of wind power especially if the balancing costs increase (Atherton, Sharma & Salgado, 2017). If intraday prices dip or peak to especially low or high numbers due to the 15-minute ISP, the battery may even be used for that. When the 15-minute ISP is implemented, a BESS will reduce costs caused by wind power forecast errors and if the market behaviour is based on intraday and day-ahead prices, the profitability of a wind farm is further increased (Cai et al., 2016). Therefore, a BESS would be even more profitable in the future.

7 Discussion

7.1 Findings on the 15-Minute ISP for an Independent Wind Power Producer

The day-ahead market is not an optimal place for a wind power producer, but there are limited options available. The main option is the power purchase agreement, which has a stable price but low price level, and there are not many buyers on the market. Another option to ensure a specific price is to sell futures, but their price level is also often low. The challenges of the day-ahead market are that there is a slight negative correlation, so when the wind power volumes are high, the day-ahead volumes are often lower and also the prices are lower. The advantages are that in 2018, large-scale, modern wind power was profitable on the day-ahead market despite the negative correlation and minor balancing costs.

The implementation of the 15-minute imbalance settlement period means that the balancing and intraday markets will transform from a one-hour to a 15-minute market time period. This reformation will increase the volatility of the intraday and balancing market prices and volumes, and it will make intermittent wind power less profitable.

If the finer time period is implemented, the volatility of intraday market volumes may increase by almost 50 %. The volatility of average intraday prices and highest intraday prices may only slightly increase, but the most significant difference is that the lowest intraday price's volatility may increase the most, and it may even double. The transformation would likely also increase the volatility of balancing market prices by up to a double. The volatility of the balancing market volumes may increase even more, by 33-244 %. However, these numbers are based on the comparison between the German and Finnish electricity markets and therefore it does not necessarily mean that the estimated outcomes will happen in Finland.

The balancing costs of wind power are relatively low, but they are expected to rise after the implementation of the 15-minute imbalance settlement period and the 1-price model. Inflexible producers are the victims of the reformation because they are the ones to pay. They will likely increase their participation in the intraday market when the quarterly intraday and balancing markets are carried out. In intraday markets, there will be most trading in the first and last quarters of each hour during which the average price volatility has been the highest. The lowest and highest prices could vary more and generally, it could become more expensive for an inflexible BRP to stay in balance, even when the BRP increases its activity in the intraday market. This new market environment and volatile intraday prices could lure demand response mechanisms and flexible power producers to shift from reserve markets to the intraday market.

7.2 Findings on the Effect of Increasing Variable Renewable Energy Sources

Variable renewable energy sources are increasing. In this study, their level of market cannibalization was estimated. A single wind turbine explained on average only 31 % of the variation of total wind power production in Finland. A single small wind farm explained on average 37 % of the variation of total wind power production in Finland. Two wind farms, 200 kilometres from each other, explained together on average 45 % of the variation of total wind power production in Finland. Both wind farms are located in non-popular places for wind power in central and eastern Finland. The results indicate that wind power production in Finland seems to be quite heterogeneous and the further wind power plants are located from each other, the less they suffer from cannibalism.

In 2018, there was a slight negative correlation of wind power production with day-ahead prices and of wind power and forecast error with intraday and balancing prices This means that the less there was wind power production or the less there was wind power production compared to the estimation, the greater the balancing costs or profits and the intraday and day-ahead prices were. And the more there was wind power production and the more there was wind power production compared to the estimation, the lower the balancing costs or profits and intraday and day-ahead prices were. There was most correlation with the day-ahead prices when wind power explained almost 5 % of them, and least correlation with balancing power prices when wind power explained 2.5 % of them. This means that the day-ahead, intraday and balancing power prices are only slightly unfavourable for a wind power producer. At these current production volumes, having only around 7 % of electricity consumption and 9 % of electricity production produced by wind power in Finland, the risk of wind power production affecting balancing costs or intraday prices is low.

The correlation between wind power production and balancing power prices has increased during all the studied years 2016 to 2017 to 2018 and the correlation between wind power forecast error and balancing power prices has increased during all the studied years 2017 to 2018 but both increases are very slight. At this pace, there will likely be no significant correlation during the next years either, but at some point, it may become an issue. Further investigation is needed to have a more reliable and specific estimate. Nevertheless, cannibalism can be minimized by having wind farms in areas of fewer wind farms, by storing electricity or by selling wind power via other methods than the power market.

Also, the distribution of regulating hours along different forecast errors was analysed, and the results show that the wind power production volume tends to be underestimated, probably because it helps to minimize balancing costs. It was also found that during the day when its usually less windy, wind power forecast error is usually negative, and during the night when it's usually windier, it is usually positive. This proves it is hard to make forecasts on the production scale extremities, and the forecast is often too modest.

7.3 Findings on Electricity Storage

Battery electricity storages are almost profitable if they are alone on the FCR-N markets. The major reason for the low profits is that if a battery is sold to the FCR-N market at all times, one third of the time the battery is unable to respond to the demand. If a battery is unable to respond, it does not only lose its profits, but it also needs to pay a fee as large as the compensation for capacity during the hour. The issue can be eased by estimating the ability of the battery on the day before and not promising to operate as FCR-N during all hours. This, however, also decreases profits since you get paid for only the time you have promised to operate.

Another solution to the issue would be charging the battery occasionally. 90% of the time when a storage is unable to respond to the demand is when it’s empty. Using excess wind power for charging the battery until a 55 % state of charge instead of selling it in the balancing power markets, increases the profitability even when the losses in balancing power markets are considered.

When the 15-minute ISP and a 1-price imbalance settlement model is implemented, the profitability of using a battery with wind power further increases. This is because the wind power producer, if acting as a balance responsible party, saves significantly in balancing costs and increased intraday prices. Therefore, for a wind power producer acting as a BRP, a BESS is already profitable, but it will likely be even more profitable in the future. Further research is needed to calculate more accurate profitability of a BESS with wind power in Finland, taking into account day-ahead and intraday prices. If an investment is made in a BESS with wind power, an algorithm is needed to manage the charging and discharging to ensure and maximize profitability.

8 Conclusions

Wind power is challenging for its balance responsible party due to its inflexibility, intermittency and inaccurate forecasting. Therefore, its profitability is very dependent on electricity markets. This thesis analysed the impact of the 15-minute imbalance settlement period together with other electricity market reformations and the potential of electricity storages for an independent wind power producer. Also, the impact of increasing variable renewable energy production was analysed.

The implementation of the 15-minute imbalance settlement period along with the one-price imbalance settlement model will make electricity markets less favourable for a wind power producer. Until now, imbalance fees have not encouraged wind power producers to stay in perfect balance. After the implementation of the one-price imbalance settlement model, wind power producers will suffer from a higher cost of purchasing and lower profits of selling electricity on the balancing power. The 15-minute imbalance settlement together with the one-price model will encourage activity on the intraday market to avoid high or low balancing prices. This will increase intraday price volatility. To some extent, intraday price formation can be estimated from day-ahead prices. Therefore, it is wise for a wind power producer to buy and sell wind power on the intraday markets before the demand increases or the lack of demand decreases the prices.

Additionally, the increasing amount of intermittent wind power will affect the electricity markets by decreasing profits on the day-ahead market and increasing costs on the intraday and balancing power markets. Spreading wind farms in different geographical locations may decrease the cannibalization effect.

Wind power producers can protect themselves from unfavourable intraday and balancing power prices by using an electricity storage, such as a battery. Lithium-ion batteries are currently not entirely profitable on the FCR-N market. The key challenge faced by batteries is an unfavourable charge and discharge cycle. Generally, the reserve market demands more discharging than charging of batteries, at times during prolonged periods, which batteries are ill-equipped to serve. This results in batteries being often empty and unable to function as required, resulting in high fees. The issue can be mitigated by charging them with excess wind power resulting from an incorrect production forecast. This could increase the profitability of a battery storage. The implementation of the 15-minute imbalance settlement period and the one-price imbalance settlement model would likely further increase the profitability of battery storages via savings in balancing and intraday costs of intermittent wind power production.

As mentioned, there will be several major challenges for a wind power producer in Finland within the next few years. Fortunately, smart and algorithmic market behaviour and the utilization of electricity storages will mitigate some of these challenges.

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